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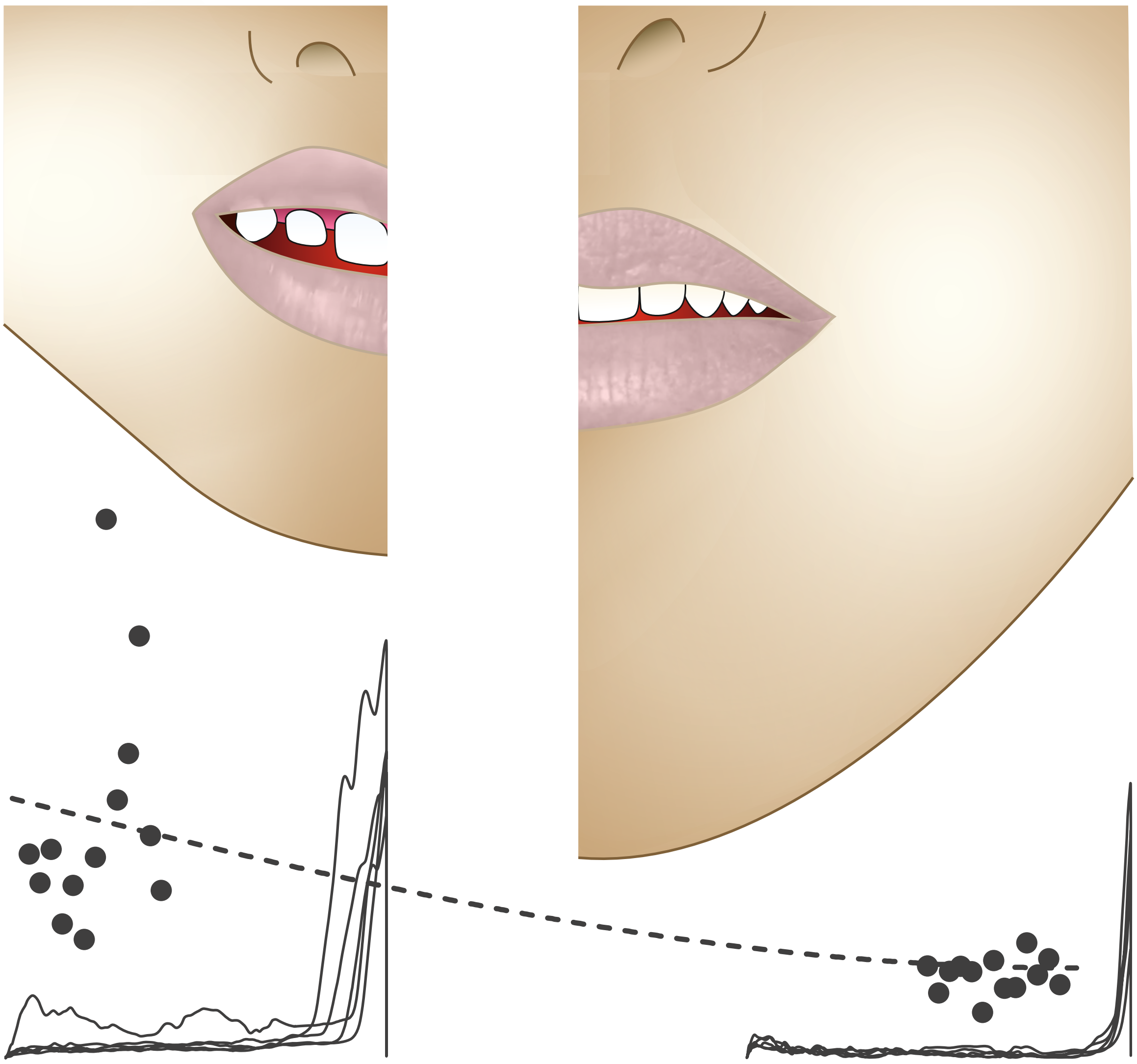
Biting and chewing behaviours in humans – Development and age-related changes



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BITING AND CHEWING BEHAVIOURS IN HUMANS – Development and age-related changes

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Stockholm 2020

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The cover image shows a magnified representation comparing a child aged 4 years and an adult aged 33 years. Hold-and-split task (Study III) undertaken by participants of identical ages, namely, 4 and 33 years of age, are exemplified by the line graphs.

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THESIS FOR DOCTORAL DEGREE (Ph.D.)

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He who perpetually pursues knowledge is a scholar, but he who believes that he has acquired all the existing knowledge is unknowledgeable

"لا يزالُ المرءُ عالماً ما طَلب العلم ، فإذا ظنَّ أنَّه قد علم فقد جهلْ"

Ibn Al Mubarak (736–797 A.D.)

To my beloved parents, brothers and sisters,
and most of all, my wife, Meshaiel, and
our two daughters Jumanah and Laila

ABSTRACT

Background: The central nervous system initiates chewing and biting behaviours, while the peripheral sensory receptors embedded in various orofacial structures (e.g. masticatory muscles, temporomandibular joint, and periodontium) are responsible for refining those behaviours. During growth, the orofacial structures are subject to significant developmental alterations, which can pose substantial difficulties to sensorimotor regulation of the behaviours of biting and chewing. In spite of this, the development of such behaviours in healthy children has been inadequately investigated.

Objectives: The overall objective of the current PhD thesis is to investigate the age-related changes of the orofacial sensorimotor control of biting and chewing behaviours in well-controlled and standardized studies of healthy children. More specifically, Study II focuses on oral force control task of unpredictable load changes, Study III focuses on food biting manoeuvre task, while Study IV focuses on chewing behavioural task of food of varying hardness. The work also seeks to distinguish key moments in the process of development and establish how and when "adult-like" biting and chewing behaviours are acquired.

Study I involved a systematic review of age-related changes in jaw sensorimotor control and objective parameters of chewing, revealing that, as the orofacial structures developed, there was a progressive transformation in chewing parameters (e.g. maximum voluntary bite force, jaw muscle activity, and jaw kinematics), which depended primarily on the status of dentition. The meta-analysis undertaken indicated that it was during the late-mixed to early-permanent dentition phases that the "adult-like" control of the above-mentioned parameters was acquired. Several studies were formulated to assess this observation through comparative analysis of healthy children and adults regarding biting and chewing behaviours. Each study employed healthy children in the age range 3-17 years old, who were allocated in the same number into five age groups corresponding to the five phases of tooth eruption, namely, primary dentition (3-5 years), early-mixed dentition (6-8 years), late-mixed dentition (9-11 years), early-permanent dentition (12-14 years), and late-permanent dentition (15-17 years). The control group used for comparative purposes consisted of healthy adults aged between 18 and 35 years old.

Study II involved a standardised force control task, which the participants (65 children and 13 adults) had to perform using their front teeth. The task was designed to explore the age-related changes in oral motor control strategies that children and adults used after unpredictable load changes. To that end, four loads were presented in a sequential and non-sequential pattern, with measurement of the front tooth forces during the activities of pulling and holding. According to the findings, children in all groups resembled adults in their ability to undertake unpredictable oral motor tasks.

Using 65 children and 13 adults, ***Study III*** involved a typical food holding-and-splitting task to gain insight into the age-related changes in oral fine motor control during food biting manoeuvres. The task entailed the participants gently holding a food morsel against a force transducer between two antagonist central incisors for an interval of 3-4 seconds and then split it. Unlike the adults, higher forces of greater variability were employed by the children with primary to early-permanent dentition (3-14 years) in the phase of food holding, whereas

food splitting was lengthier in children with primary and early-mixed dentition (3-8 years) compared to adults.

Sixty children and ten adults were employed in ***Study IV*** to determine how chewing behaviour was affected by food of varying hardness. This involved recording the jaw kinematics and jaw muscle activity associated with the masseter muscle whilst the participants ate three soft and three hard viscoelastic test food models. Unlike adults, children with primary and mixed dentition (3-11 years) exhibited a significant increase in tooth occlusal duration at the end of the chewing sequence when they ate hard food. Meanwhile, no adaptation in jaw muscle activity to food hardness was observed in children with primary to early-permanent dentition (3-14 years) by comparison to adults. Children with late-permanent dentition (15-17 years) did not display such discrepancies as adult-like jaw kinematics and jaw muscle activity were attained by that stage.

Conclusion: The studies conducted in this doctoral thesis suggested that young healthy children were capable of basic biting and chewing behaviours, but they differed from adults in terms of biting force control and adaptation of jaw kinematics and jaw muscle activity when they chewed food of varying hardness. Taken together, such discrepancies could reflect age-related development of oral sensorimotor control of chewing and biting behaviours. Complete development of orofacial structures must occur before an adult-like biting and chewing behaviour is attained.

LIST OF SCIENTIFIC PAPERS

I. **Almotairy N**; Kumar A; Trulsson M; Grigoriadis A
Development of the jaw sensorimotor control and chewing - a systematic review
Physiology & Behavior. 2018; 194:456–465
DOI: 10.1016/j.physbeh.2018.06.037

II. **Almotairy N**; Kumar A; Welander N; Grigoriadis A
Age-related changes in oral motor-control strategies during unpredictable load demands in humans
European Journal of Oral Sciences. 2020; 128(4):299–307
DOI: 10.1111/eos.12721

III. **Almotairy N**; Kumar A; Noirrit-Esclassan E; Grigoriadis A
Developmental and age-related changes in sensorimotor regulation of biting maneuvers in humans
Physiology & Behavior. 2020; 219:112845.
DOI: 10.1016/j.physbeh.2020.112845

IV. **Almotairy N**; Kumar A; Grigoriadis A
Effect of food hardness on chewing behavior in children
Clinical Oral Investigations. 2020; 00:1–14
DOI: 10.1007/s00784-020-03425-y

CONTENTS

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CNS	Central nervous system
EMG	Electromyography
Emtree	Embase Subject Heading (Embase)
MeSH	Medical Subject Heading (PubMed/Medline)
MOBF	Maximum occlusal bite force
N	Newton
PMRs	Periodontal mechanoreceptors
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
RMS	Root mean square
SD	Standard deviation
TMJ	Temporomandibular joint

1 INTRODUCTION

During the past decades, the field of orofacial neuroscience evolved as a well-respected branch of neuroscience with rich literature (Iwata & Sessle, 2019). The emergence of orofacial neuroscience drove many studies that provided new insights and better understanding into the sensorimotor control of several orofacial behaviours such as biting, chewing and salivation. New insights have been also gained about the neural pathways and brain circuits underlying each of these functions, as well as the role of non-neuronal processes and plasticity in modifying these functions, in adapting tissue injury and pain and in learning or rehabilitating oral and facial functions (Kumar *et al.*, 2018).

The human chewing behaviour is a sensorimotor behaviour of high complexity, benefitting the body by activating food digestion through fragmentation of food, which makes it easier to swallow (van der Bilt *et al.*, 2006; Chen, 2009), as well as improving taste and texture perception of various foods (Chen, 2009), and contributing to preservation of oral health by enhancing saliva production (Dodds *et al.*, 2015). Hence, impaired chewing can have adverse implications for food fragmentation capability, food ingestion (Sheiham & Steele, 2001; Watson *et al.*, 2019), nutrition (Watson *et al.*, 2019) and the quality of life of affected individuals (Brennan *et al.*, 2008). The central nervous system (CNS) initiates the chewing mechanism, while sensory receptors in a number of orofacial structures (e.g. masticatory muscles, temporomandibular joint [TMJ], oral mucosa, periodontium) are responsible for refining that mechanism (Dellow & Lund, 1971; Lund, 1991, 2011; Westberg & Kolta, 2011; Morquette *et al.*, 2012). Earlier studies have reported that the mechanoreceptors withing the periodontal ligaments could be crucially informative regarding the spatial and temporal aspects of food (Trulsson & Johansson, 1996a, 1996b), thereby assisting the CNS in initiating and modulating biting and chewing behaviours (Trulsson & Johansson, 1996a, 1996b; Trulsson & Gunne, 1998; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009, 2011; Grigoriadis *et al.*, 2011, 2014, 2019; Kumar *et al.*, 2014, 2015, 2019; Grigoriadis & Trulsson, 2018).

Childhood is a period when, ideally, the sensorimotor control mechanisms adapt to the alterations in proportions and development that the body goes through. Such adaptation is challenging for the CNS. For instance, there is evidence that the motor control of human precision grip undergoes age-related changes and it is in the age range 8-11 years old that “adult-like” motor control is accomplished (Forssberg *et al.*, 1991, 1992, 1995; Gordon *et al.*, 1992; Eliasson *et al.*, 1995). It is notable that, as the human precision grip develops with age, it changes from motor control based mainly on feedback to motor control that is more mature and based on anticipatory feedforward (Forssberg *et al.*, 1992, 1995).

Development is accompanied by considerable orofacial structure alterations. The lengthy process of transition from primary to permanent dentition involves significant changes to the craniofacial form and function. Hence, the CNS may be faced with the necessity to regulate systems characterised by dynamic variation due to the extensive temporal fluctuations in skeletal mass and form and in muscle mass and geometry. Regarding oral motor control for speech, it has been found that speech movement trajectories vary more acutely in children aged 16 years than in young adults. Furthermore, it appears that adult-like speech motor behaviour is acquired relatively late (Walsh & Smith, 2002). This leads to the premise that, during growth, considerable difficulties are associated with the sensorimotor control of chewing behaviour and this behaviour has to adjust in keeping with orofacial structure transformations. The present work tests this premise by conducting well-controlled and standardised studies comparing changes in the sensorimotor control of biting of chewing behaviours in healthy children and adults.

1.1 NEURAL CONTROL OF BITING AND CHEWING BEHAVIOURS

Chewing typically starts by placing the food morsel into the mouth and positioning it between the teeth. The food morsel is then crushed into smaller pieces using the teeth and mixed with the saliva to form a cohesive and moisturized bolus that is suitable for swallowing (van der Bilt, 2009). Hence, chewing is a critical function ensuring that food is swallowed safely and activating the process of digestion (Chen, 2009). The chewing behaviour is a semi-voluntary, intermittent and rhythmic jaw movement, where the movement of other structures such as the lips, tongue, and the jaw muscles is well-coordinated to achieve a successful chewing behaviour and to avoid potential tissue harm. Research on animal models has revealed that motor neurons from specialised neural circuits within the pons and medulla of the brainstem known as the masticatory central pattern generator are in charge of automatic activation and fine-tuning of the inherent rhythmical neural patterns involved in biting and chewing (Dellow & Lund, 1971; Lund, 1991, 2011; Westberg & Kolta, 2011; Morquette *et al.*, 2012). Furthermore, the primary motor cortex and the primary somatosensory cortex may both be capable of inducing the masticatory rhythmic activation (Sessle *et al.*, 2005; Sessle, 2011). Proprioceptive feedback may not be required for such alternative rhythmic activation of the jaw-opening and -closing muscles (Morquette *et al.*, 2012). On the other hand, uninterrupted peripheral sensory signals issued by mechanoreceptors in various orofacial structures are essential to regulate the motor output that is produced (Dellow & Lund, 1971; Lund, 1991, 2011; Trulsson & Johansson, 1996a, 1996b; Trulsson & Gunne, 1998; Trulsson, 2006; Westberg & Kolta, 2011; Morquette *et al.*, 2012). The CNS exploits these signals to establish suitable muscle forces according to the physical properties of the food (Peyron *et al.*, 2002; Grigoriadis *et al.*, 2011, 2014, 2019; Grigoriadis & Trulsson, 2018). Additionally, motor program modulation in line with food properties during chewing is achieved through the use of sensory signals of the same mechanoreceptors in feedback or anticipatory feedforward patterns (Dellow & Lund, 1971; Lund, 1991; Trulsson & Johansson, 1996b, 1996a; Trulsson & Gunne, 1998; Lund & Kolta, 2006; Trulsson, 2006; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009, 2011; Grigoriadis *et al.*, 2011; Westberg & Kolta, 2011).

1.2 SENSORY RECEPTORS INVOLVED IN THE ACT OF BITING AND CHEWING

1.2.1 Mechanoreceptors in the masticatory muscles

The masticatory muscles resemble other skeletal muscles in that they use the proprioceptive sensory input from receptors (e.g. muscle spindles, Golgi tendon organs) for mediation of their structure in the context of regular chewing behaviour.

1.2.1.1 *Muscle spindles*

Located in the muscle belly, the specialised group of mechanoreceptors represented by muscle spindles keep track of muscle length alterations. All muscle spindles organized in parallel to the extrafusal fibres and are made up of several intrafusal nuclear-chain and nuclear-bag fibres enveloped in a connective tissue capsule. Two sensory neurons of type I and type II are associated with these intrafusal fibres (Hulliger, 1984; Miles, 2004). The trigeminal mesencephalic nucleus contains the cell bodies of the sensory fibres that supply the muscle spindles of the masticatory muscles (Lund, 2011; Morquette *et al.*, 2012). Comprising gamma and beta motor neurons, the fusimotor neurons are the motor neurons linked to the muscle spindles (Burke *et al.*, 1973; Hulliger, 1984; Miles, 2004). The extrafusal muscle fibres are supplied by a series of alpha motor neurons as well (Miles, 2004).

In humans, the muscles engaged in jaw closure (e.g. masseter muscle) contain muscle spindles, whereas the muscles engaged in jaw opening do not (Kubota & Masegi, 1977; Lennartsson, 1979). Furthermore, the muscle spindles in jaw-closing muscles may contribute significantly to muscle proprioceptive control during biting and chewing behaviours because of the multitude of intrafusal fibres they encompass (Eriksson *et al.*, 1994). Stretching of both the muscle spindles and extrafusal fibres occurs alongside muscle stretching in biting and chewing. Type I and type II afferent neurons transmit sensory signals to the CNS when the muscle spindles are stretched. Subsequently, the alpha motor neurons are stimulated by the CNS, leading to contraction of the extrafusal fibres and muscle spindle shortening, the latter in turn resulting in a reduction in the spindle sensory output. Stimulation of the gamma motor neurons also occurs to avoid the muscle spindles becoming inactive when the muscle contracts. The rate of contraction of the intrafusal and extrafusal fibres is the same owing to gamma motor neuron stimulation. Consequently, the activity of gamma motor neurons contributes to the maintenance of muscle contraction by triggering a spindle sensory input even during muscle contraction.

1.2.1.2 *Golgi tendon organs*

Muscle attachment to bone is mediated by tendons comprising proprioceptive sensory receptors known as Golgi tendon organs, which can send information to the CNS regarding muscle tension alterations. Just one myelinated Ib sensory supplies every Golgi tendon organ. From a functional perspective, every organ displays sensitivity to low forces and achieves saturation at elevated forces (Jami, 1992). Nevertheless, no extensive research has been conducted on the Golgi tendon organs in masticatory muscles. Although earlier studies confirmed that cat masseter and temporalis muscles did contain such organs (Hamada *et al.*, 1974; Lund *et al.*, 1978), their occurrence in humans has not been investigated, so there is no available knowledge about how the Golgi tendon organs are physiologically involved in biting and chewing behaviours.

1.2.2 Mechanoreceptors in the TMJ

Free nerve endings, Golgi organs, Pacinian corpuscles, and Ruffini nerve endings are among the receptors present in the TMJ capsule (Dixon, 1962; Thilander, 1964), with the trigeminal ganglion containing the receptor cell bodies (Lund & Matthews, 1981). According to earlier suggestions, the motion of the jaw during biting and chewing behaviours may be regulated with the involvement of such sensory receptors (Klineberg, 1980; Lund & Matthews, 1981). Nevertheless, the input of the receptors is considered to be restricted mainly to the avoidance of joint displacement in extreme jaw motions (e.g. jaw opening, lateral, and forward protrusion movements) (Sessle, 2006).

1.2.3 Mechanoreceptors in facial skin, lips, and oral mucosa

The introduction of the microneurographic method (Vallbo & Hagbarth, 1968) has made it possible to collect data from a range of human peripheral nerves. This method permitted documentation of the encoding properties and receptive field of low-threshold single afferents from various orofacial mechanoreceptors in the context of normal orofacial behaviours. The four mechanoreceptive afferents that have been distinguished in the soft tissue of orofacial structures show a behaviour that does not differ much from the behaviour of the human hand from a functional perspective. More to the point, hair follicle afferents, slow adapting (SA) type I (Merkel's disk) and type II (Ruffini) afferents, and fast adapting (FA) type I (Meissner corpuscles) afferents are all present in orofacial structures (Johansson, Trulsson, Olsson, & Westberg, 1988; Edin *et al.*, 1995; Trulsson & Essick, 1997; Trulsson & Johansson, 2002; Bukowska *et al.*, 2010). The CNS exploits the receptors in the facial skin, lips, and oral mucosa to signal information about the interaction between orofacial structures and external objects such as food (exteroceptors).

The ratio of SA to FA afferents is not the same in all orofacial structures. For example, the facial skin, vermilion border, and oral mucosa of the lips contain mostly SA afferents (Trulsson & Johansson, 2002; Essick & Trulsson, 2008), while the tip of the tongue contains primarily FA afferents (Trulsson & Essick, 1997; Trulsson & Johansson, 2002; Essick & Trulsson, 2008; Bukowska *et al.*, 2010). This difference in the ratio of SA to FA afferents reflects discrepancies in the functional characteristics associated with the various structures. For instance, active contact with objects may depend significantly on the elevated proportion of FA afferents in the tongue tip, whilst the afferents in the facial skin, lips, and buccal mucosa serve as exteroceptors and are informative regarding facial skin and oral mucosa distortion caused by the lip and jaw motion during biting and chewing and by modifications in the air pressure in the mouth during speech utterance (Johansson, Trulsson, Olsson, & Abbs, 1988; Trulsson & Johansson, 2002).

1.2.4 Periodontal mechanoreceptors

The roots of the teeth are lodged into the surrounding bony structure by periodontal ligaments, which contain free nerve endings known as periodontal mechanoreceptors (PMRs) (Cash & Linden, 1982; Byers, 1985; Linden & Scott, 1989). PMRs are most abundant in the apex of the roots, although they are also dispersed around the roots. Classified as SA type II receptors, PMRs are similar to the Ruffini receptors in the hand glabrous skin. Furthermore, they are tactile receptors of high sensitivity that are informative of periodontal ligament stretching associated with tooth loading (Trulsson & Johansson, 1996a). In terms of histology, PMRs exhibit considerable morphological variability, although they are innervated by myelinated nerve fibres, the cell bodies of which are located in the trigeminal ganglion or the trigeminal mesencephalic nucleus (Beaudreau & Jerge, 1968; Gottlieb *et al.*, 1984; Linden & Scott, 1989).

The microneurographic method has been effectively employed in earlier research on human subjects to document neural signals of one periodontal afferent from the inferior alveolar nerve (Trulsson & Johansson, 1994, 1996a). There is evidence of automatic discharge and gradual adaptation of PMRs to persistent tooth loading, with most receptors exhibiting high sensitivity to low forces of less than 1 N and less than 4 N for anterior and posterior teeth, respectively (Trulsson & Johansson, 1994; Johnsen & Trulsson, 2005; Trulsson, 2006; Johnsen *et al.*, 2007). Furthermore, sensory information regarding the temporal, spatial, and intensive properties of tooth loading is signalled by the PMRs (Trulsson, 2006). However, the majority of these receptors rapidly saturate during excessive force levels, thus poorly encode the force magnitude (Trulsson, 2006). Such research results promoted the premise that PMRs may be involved in the force magnitude specifications and point of attack during the first contact with food and during additional force adaptation of biting and chewing behaviours (Trulsson & Johansson, 1996b). A specially developed system of food holding and biting (hold-and-split task) was used to explore the premise, revealing that PMRs were actually critical in the initial food contact during biting and chewing (Trulsson & Johansson, 1996a). Wherein, the motor command to the masticatory muscles is adapted based on the varying mechanical properties of the food. The loss of PMR signals as a result of anaesthetic inhibition or substitution of natural teeth with a prosthesis (e.g., dental implants) causes disruption of this mechanism of adaptation, with production of more elevated forces of greater variability (Trulsson & Gunne, 1998; Svensson & Trulsson, 2009, 2011; Kumar, Castrillon, *et al.*, 2017).

1.3 CHANGES IN THE MASTICATORY APPARATUS IN GROWING CHILDREN

Various orofacial structures contain the sensory receptors underpinning the chewing activity, as discussed earlier. During growth, the morphology of these structures goes through changes in relation to age. It can therefore be implied that children are required to acquire and adjust oral sensorimotor control during biting, chewing, and other regular motor behaviours according to orofacial structure transformations.

The jaws are flat in human new-borns and subsequently undergo age-related increase, expanding in the three-dimensional planes. The jaws width significantly increases from age two and experience stable growth until 10-14 years of age (Bishara *et al.*, 1997). It has been discovered that the human jaws elongate in a two-phase pattern of development, in line with the exponential increase in jaw width (Kelly *et al.*, 2017). These two phases of jaw elongation occur between birth to around five years of age and during the growth spurt associated with puberty. Likewise, the TMJ and articular eminence are flat in new-borns and then undergo modifications related to age. The fully-developed S-shaped morphology of the articular eminence emergences at 6-7 years of age, whilst complete development of the TMJ occurs after puberty (Keith, 1982). An earlier study made a notable remark regarding the fact that the jaw height and width were closely correlated with the chewing cycle duration (Gerstner *et al.*, 2014), with the chewing ability of children aged 10-14 years being identical to that of adults.

It is not only the jaws that undergo transformations as human growth unfolds, but the teeth as well. In general, the primary dentition emerges first before being replaced by the permanent dentition. The eruption of the initial primary tooth occurs at 6-10 months of age and the other primary teeth then follow suit. From a functional perspective, the primary dentition achieves stability in the age interval 30 months to six years old, after which it starts its transition that goes on until around age 12. There is evidence that a close correlation exists between human dentition development and the ability to effectively fragment food (Brennan *et al.*, 2008) and this correlation is associated with transformations in the pattern of jaw movement. During chewing, this pattern differs in healthy children and adults (Wickwire *et al.*, 1981; Gibbs *et al.*, 1982; Saitoh *et al.*, 2004, 2010). More specifically, in healthy children, the pattern is distinguished by a broad and laterally directed jaw opening path and subsequently a more centric jaw closing path, whilst in adults, the pattern starts with a centric and vertically directed jaw opening path and subsequently a laterally directed jaw closing path. It is possible that the skeletal modifications in the jaws, and TMJ and the discrepancies between primary and permanent teeth regarding the occlusal table may be the causes of the dissimilarities of the jaw movement pattern in children and adults. It has been notably observed that the adult-like jaw movement pattern is acquired by children at about 12 years of age, when the eruption of the permanent canines occurs (Wickwire *et al.*, 1981; Gibbs *et al.*, 1982).

When the primary dentition transitions to the permanent one, the periodontal structures undergo changes in relation with age. For instance, the roots of the primary teeth are resorbed and the roots of the permanent teeth start to develop. The alterations in structure may reflect accompanying modifications and realignment of the periodontium and periodontal receptors. Although, human studies on transformations in histology and PMR maturity are not available, studies conducted on animals have revealed histological alterations associated with age in how PMRs were distributed and morphologically constituted (Maeda *et al.*, 1999; Shi *et al.*, 2006; Umemura *et al.*, 2010; Miki *et al.*, 2015). The distribution of PMRs has been found to be denser in the permanent teeth than in the primary ones (Umemura *et al.*, 2010; Miki *et al.*, 2015). Furthermore, it has been noted that full receptor development was correlated with tooth eruption and formation of mechanical occlusal force (Maeda *et al.*, 1999). Due to this correlation, PMR morphology matures slower when a particular tooth has low occlusal forces, as happens in the case of tooth grinding (Shi *et al.*, 2006). Hence, it can be indicated from this evidence that PMRs may have a scant distribution in human primary dentition and maturation of tooth occlusion in permanent dentition may be a prerequisite for PMR morphology developing fully.

Transformations in the structure of the masticatory muscles occur alongside the age-related transformations in the skeletal and dental structures. Evidence from previous studies indicates that, in healthy individuals, the masseter muscle thickens considerably during the interval between primary and early-mixed dentition (Castelo, Pereira, *et al.*, 2010) and between mixed dentition and adulthood (Palinkas *et al.*, 2010). The masseter muscle consists of a unique fibre-type composition in young children of 3-7 years of age compared to adults (Österlund, Thornell, *et al.*, 2011). Such modifications are reflected by the fact that muscle fibres have an increased diameter and are more numerous in adults than in young children. There is a possibility that the histological discrepancies in the fibres of the masseter muscle may suggest that young children and adults are dissimilar in terms of the properties of contraction of the masticatory muscles (e.g. muscle strength and power). Earlier studies found that, compared to adults, the highest bite force in children of 5-7 years of age was approximately 50% lower (Braun *et al.*, 1996; Castelo, Pereira, *et al.*, 2010; Palinkas *et al.*, 2010). On the other hand, there is not much difference between children aged 3-7 years and adults regarding the manner in which masseter muscle spindles are structured and distributed (Österlund, Liu, *et al.*, 2011). The fact that the masseter muscle spindles achieve full development at an early age may imply an increase demand for children to acquire and fine-tune oral motor activities (e.g. chewing, biting, speaking).

Numerous studies have been conducted on the sensorimotor control of chewing and biting behaviours in adults, but studies on healthy children are not adequate. On the other hand, research on other motor behaviours in children (e.g. finger precision grip, walking, speaking) have indicated that the development of such behaviours is associated with age (Sutherland *et al.*, 1980; Forssberg *et al.*, 1991; Walsh & Smith, 2002). Drawing on such research, it can be hypothesized that the extensive transformations undergone by orofacial structures during growth could present difficulties to the sensorimotor control in the context of oral behaviours like biting and chewing. Another viable hypothesis is that the modifications in the oral sensorimotor control of biting and chewing in young children are associated with age and complete structure development is a prerequisite for attaining adult-like biting and chewing behaviours.

1.4 AIMS OF THE PRESENT THESIS

1.4.1 General aim

The present work sought to undertake well-controlled and standardised studies to investigate the normal development and age-related changes undergone by the orofacial sensorimotor mechanism underpinning the regulation of biting and chewing behaviours in healthy children. Another concern was to gain insight into the key points of development and the learning of adult-like biting and chewing behaviours.

1.4.2 Specific aims

Study I

An assessment of the existing evidence regarding the development of the jaw sensorimotor control and chewing in healthy children was carried out by a systematic review of the related literature. Four well-known chewing parameters were investigated for modifications related with age, namely, maximum occlusal bite force (MOBF), chewing jaw electromyography (EMG), jaw kinematics, and chewing efficiency.

Study II

The second study involved a standardised force control task for investigation of the age-related changes in oral motor control in relation to unpredictability in load changes, as well as comparative analysis of the identified strategies in children and adults.

Study III

The third study involved a standardised food hold-and-split task for comparative analysis of age-related changes in oral fine motor control in children and adults.

Study IV

The fourth study involved a standardised task of chewing behaviour of viscoelastic test food models of varying hardness for comparative analysis of age-related changes in jaw kinematics and jaw muscle activity in children and adults.

2 MATERIALS AND METHODS

2.1 CURRENT EVIDENCE OF JAW SENSORIMOTOR CONTROL AND CHEWING IN HEALTHY CHILDREN (STUDY 1)

2.1.1 Sources of information

The protocol for the systematic review complied with the PRISMA-P guidelines (Moher *et al.*, 2015) and was registered in PROSPERO (CRD42017069760). The strategy for the search of the databases Medline (Ovid), Embase.com, and Web of Science Core Collection was devised and applied till March 2018 by Carl Gornitzki and Sabina Gillsund, who were qualified librarians working in the university library of the Karolinska Institutet. Pertinent free-text terms were used to supplement the distinguished MeSH/Emtree terms. When suitable, the terms were truncated and/or merged with proximity operators. Besides the search of the databases, Google Scholar, grey literature from the Open Grey database, and the backward and forward citations in the reviewed studies were manually searched as well. Further, no restrictions were put on the publication date and type.

2.1.2 Selection of studies satisfying the eligibility criteria

The outcomes of the database search process were transferred to EndNote, with elimination of duplicates. The final list was transferred to a pre-established Excel template. The eligibility criteria outlined in Table 1 were applied by the authors Nabeel Almotairy and Abhishek Kumar to undertake separate screening of the titles and abstracts of the studies on the final list. Studies were thus labelled as included, excluded or undecided. The authors addressed together any lack of consensus about study inclusion and/or sought the opinion of another author if required. The final list of studies for review was refined through close reading of the complete text of the selected studies. As before, the authors jointly addressed inconsistencies regarding study inclusion and/or requested the input of a third author. Original authors were contacted if any study needed further clarifications.

Table 1. The eligibility criteria applied during study selection.

Inclusion	Exclusion
• Studies addressing the considered chewing parameters of MOBF, EMG, jaw kinematics, and chewing efficiency • Studies on healthy children, regardless of comparative analysis with healthy adults	• Studies on healthy children with abnormal orofacial features or dysfunctions • Studies assessing mastication through subjective measures, such as questionnaires • Non-original studies or studies not written in the English language

2.1.3 Quality assessment and data extraction of the included studies

The instruments for critical assessment developed by the Joanna Briggs Institute were employed to evaluate not only how reliable and relevant the selected studies were, but also their results (Moola *et al.*, 2017). The chosen studies were evaluated for quality separately by the two authors and lack of consensus was discussed jointly and/or the opinion of a third author was sought. When possible, extraction and compilation of the data related to the examined chewing parameters from the selected studies were carried out.

2.2 RECRUITMENT OF PARTICIPANTS (STUDIES II-IV)

Studies II-IV were each initiated only after they were ethically approved by the Swedish Ethical Review Authority in Stockholm (Dnr: 2018/726-31/2). Emmanuelle Esclassan and Nadia Welander, two pedodontists with experience, made contact with healthy children of 3-17 years of age who presented to the Pedodontics Specialist Clinics at Karolinska Institutet, Sweden, for a dental examination, alongside their legal guardians. Upon completion of the examination, the pedodontists provided information about the research to the children and their legal guardians. Once an agreement was reached, the main researcher (Nabeel Almotairy) contacted the participants who satisfied the eligibility criteria and conducted a clinical assessment of the status of tooth eruption in every participant. Based on the outcomes of that assessment, the participants were allocated to one of five dental age groups, namely, primary, early-mixed, late-mixed, early-permanent, and late-permanent dentition (Figure 1). A control group was also recruited, consisting of healthy adults aged 18-35 years. None of the participants had any health conditions or illnesses and they were average in terms of body mass. The participants were subjected to a clinical oral examination to confirm that they did not have any active carious lesions, dental implants, moderate-to-severe malocclusion, active orthodontic treatment or fixed retainer. The empirical work was performed in accordance with the principles of the Declaration of Helsinki II. Before commencing the work, all the participants, including the children with their legal guardians and the adult participants, were required to sign a consent form.

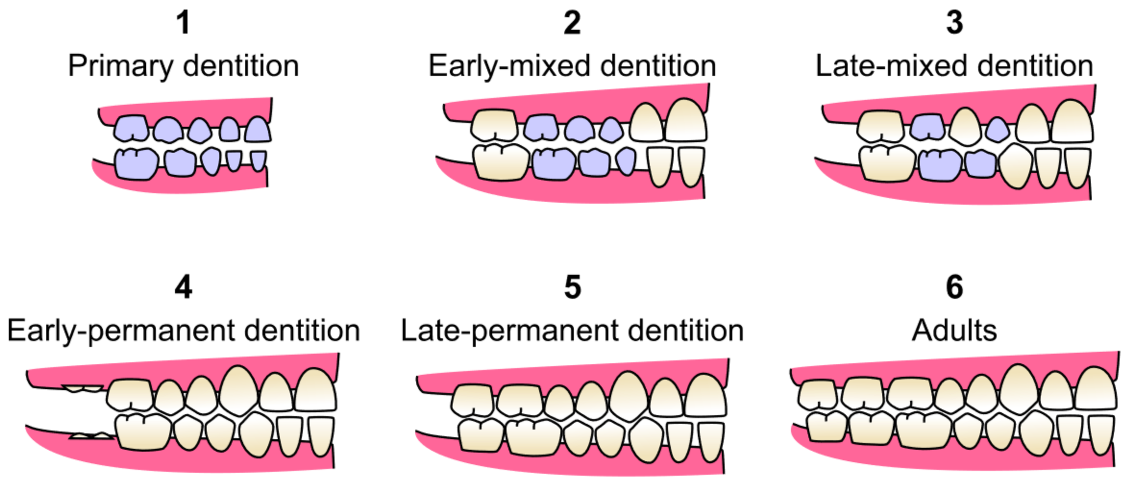


Figure 1. Simplified representation of the criteria underpinning participant classification into five dental age groups. Primary dentition consists solely of primary teeth; early-mixed dentition is defined by the eruption of the permanent first molars and a few or all permanent incisors; late-mixed dentition is defined by the eruption of the permanent premolars or canines; early-permanent dentition is defined by the eruption of all permanent teeth aside from the permanent second and third molars; and late-permanent dentition is defined by the eruption of all permanent teeth aside from the permanent third molars. In addition, the adult group refers to the full development of the permanent dentition.

2.3 STUDY PARTICIPANTS AND PROTOCOL

Study II

The second study employed 65 healthy children of 3-17 years of age, who were equally separated into five dental age groups according to their status of tooth eruption (Table 2). For comparison purposes, the study also employed a control group of 13 healthy adults of 18-35 years of age. The participants were asked to undertake an oral force control task that required them to pull and hold a force transducer resting on a platform and linked “pully-like” to a number of loads that were randomly changed, either sequential or non-sequential. The sequential loading involved application of four loads (50, 100, 200, and 300 gm) in increasing order of heaviness, while non-sequential loading involved application of the same four loads but in an arbitrary order of heaviness (100, 200, 50, and 300 gm). Under both conditions, every load mass was pulled thrice prior to moving to the next load mass. For all the loads and load conditions, a total of 24 trials were conducted.

Study III

The third study involved a standardised task of food holding and splitting that was performed by 65 children divided equally into five dental age groups (Table 2). The task consisted of holding and splitting half a peanut resting on a force transducer for a total of five training trials and five experiment trials. A control group comprising 13 adults was employed for comparison purposes. Most children (~93.4%) involved in this study also took part in Study II, and additionally, there were four children who took part either in Study II or Study III.

Study IV

This study involved 50 children of 3-17 years of age who were equally separated into five dental age groups (Table 2). A magnetic jaw tracker was used to measure jaw kinematics, while an electromyographic device was used to measure jaw muscle activity of the bilateral masseter muscle during a task requiring the participants to eat three hard and three soft viscoelastic test food models. A control group consisting of adults of 18-35 years of age was used for comparison purposes.

Table 2. The number and mean age (SD) of participants involved in Study II, Study III, and Study IV; female and male individuals respectively denoted by ♀ and ♂.

#	Group	Study number	Number of participants	Mean age (years)	SD (years)
1	Primary dentition	Study II	13 (5 ♂; 8 ♀)	4.90	0.82
		Study III	13 (4 ♂; 9 ♀)	4.87	0.80
		Study IV	10 (4 ♂; 6 ♀)	5.33	0.35
2	Early-mixed dentition	Study II	13 (8 ♂; 5 ♀)	7.74	0.84
		Study III	13 (8 ♂; 5 ♀)	7.74	0.84
		Study IV	10 (5 ♂; 5 ♀)	8.03	0.74
3	Late-mixed dentition	Study II	13 (10 ♂; 3 ♀)	11.14	0.84
		Study III	13 (9 ♂; 4 ♀)	10.99	0.90
		Study IV	10 (8 ♂; 2 ♀)	11.04	0.87
4	Early-permanent dentition	Study II	13 (4 ♂; 9 ♀)	13.32	0.83
		Study III	13 (4 ♂; 9 ♀)	13.32	0.83
		Study IV	10 (4 ♂; 6 ♀)	13.28	0.99
5	Late-permanent dentition	Study II	13 (10 ♂; 3 ♀)	16.28	0.75
		Study III	13 (10 ♂; 3 ♀)	16.28	0.75
		Study IV	10 (8 ♂; 2 ♀)	16.33	0.77
6	Adults	Study II	13 (9 ♂; 4 ♀)	25.45	4.22
		Study III	13 (8 ♂; 5 ♀)	25.22	4.92
		Study IV	10 (6 ♂; 4 ♀)	25.97	4.18

2.4 EQUIPMENTS AND EXPERIMENTAL PROCEDURES

Study II

The specially designed apparatus employed in this study was based on the ideas of earlier studies (Forssberg *et al.*, 1991, 1992) (Figure 2A) and was made of a customised force transducer (Umeå University, Physiology Section, IMB, Umeå, Sweden) with an aluminium handle that is connected to two duralumin blocks ending in two parallel inferior and superior then plates (Trulsson & Johansson, 1996a). The transducer was supported by a flat platform and tied with a string with a diameter of 0.25 mm and capable of a strength of 5 kg (Master Line Kayoba, Jula AB, Skara, Sweden). The string went through a pulley and was tied to a metal hook, which was capable of receiving a number of standardised metallic load masses (Viktsats, Sagitta Pedagog AB, Mariestad, Sweden). The forces applied on the force transducer's upper plate were similar irrespective of the point of force application on the plate.

Prior to experiment commencement, the participants were shown a video of the task in question being carried out by a child. Two black lines were respectively drawn on the handle of the transducer and on the flat platform, at a distance of 5.5 cm. The participants had to use their front teeth to bite and pull the force transducer and match the two black lines. They had to restore the transducer to its initial position following an interval of 4-5 seconds. To help them become acquainted with the task, the participants underwent a five training trials that required them to pull a load mass of 50 gm. Once the training was completed, the participants randomly began the task with the sequential or non-sequential load condition (Figure 2B), but they did not know the order in which the loads were applied. Moreover, an opaque screen was used to prevent the participants from seeing the load changing process.

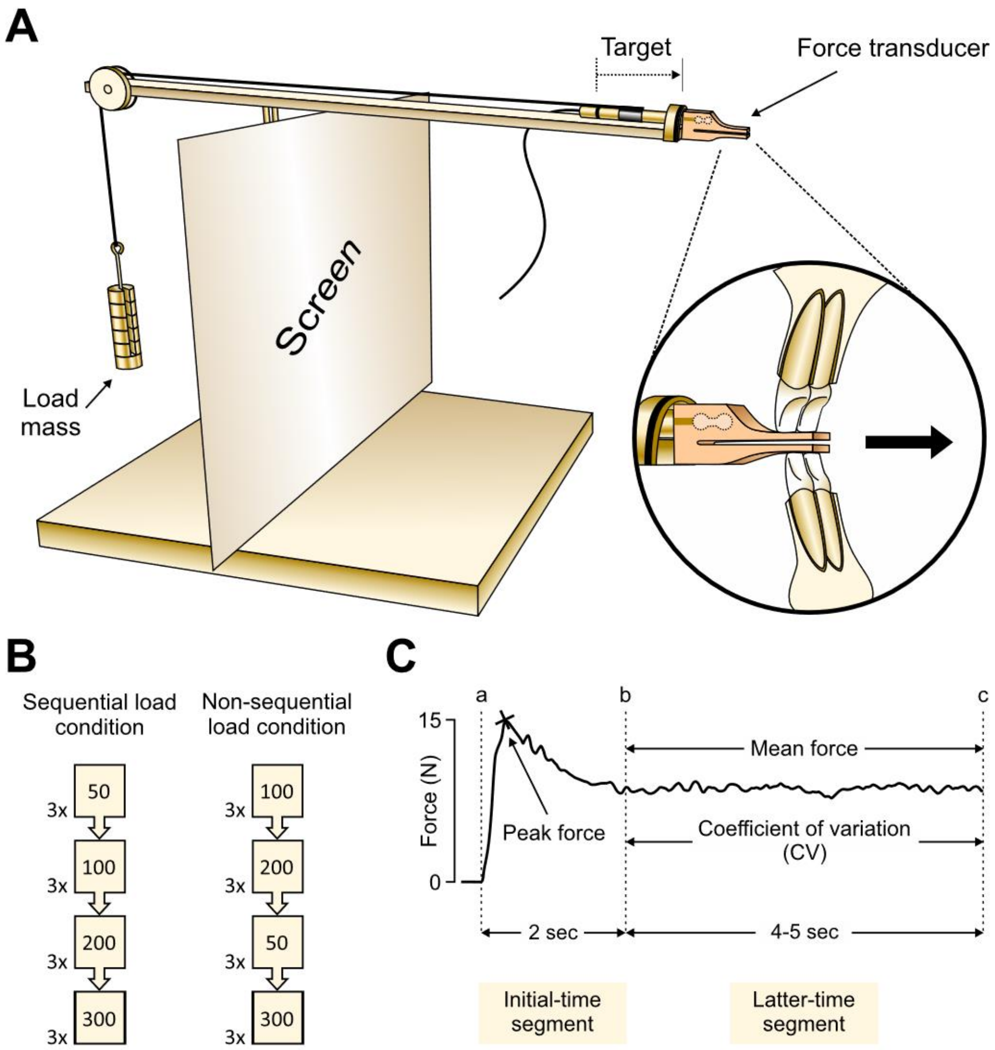


Figure 2. (**A**) Schematic representation of the oral motor control task performed with a force transducer supported on an adjustable platform. The string tying the force transducer goes through a pulley and is tied to a metal hook, which can receive a number of load masses. The participants had to use their front teeth to bite and bull the force transducer and match the two black lines for a period of 6-7 seconds, in keeping with pre-established load conditions. (**B**) The load masses were applied arbitrarily, in sequential or non-sequential order. (**C**) The general temporal force profile yielded by one oral force control task, with lines a-b and lines b-c respectively denoting the initial time-segment and the latter time-segment. In the former, the peak force was the outcome variable measured, while in the latter, the mean force (holding force) and coefficient of variation (force variability) were the outcome variables measured.

Study III

The third study employed the same device as the second study, with the exception that the remaining device components were eliminated (Figure 3A). As outlined in previous research [14, 16-19, 24, 25], the task involved holding and splitting a food morsel placed on the force transducer. The main researcher (NA) used a video of the task conducted by a child to explain what the task entailed. To facilitate its placement on the inferior front teeth, a grooved plexiglass was glued to the inferior plate of the force transducer, while a peanut half was put on the terminal end of the superior plate (Estrella TM, Estrella AB, Sweden). The participants had to keep the food morsel gently between two antagonist central incisors and split it after 3-4 seconds. The participants underwent five training trials and then five experimental trials.

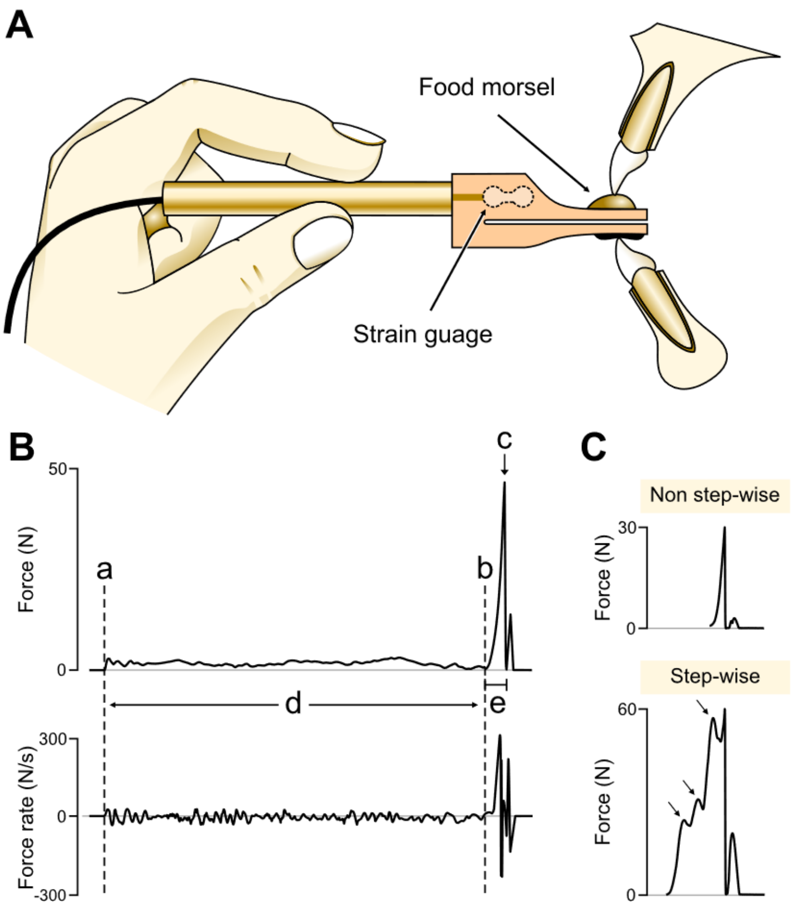


Figure 3. (**A**) Schematic representation of the task of food morsel holding and splitting, whereby participants had to gently hold the peanut half on the force transducer terminal end between two antagonist central incisors and split it after 3-4 seconds. (**B**) The temporal force profile yielded by one task of holding and splitting. The start of the food holding and splitting phases are respectively indicated by time-point (a) and time-point (b). At the start of the splitting phase, the rate of force exceeded 5 N/s, with rapid increase that resulted in the peanut being split (c). The outcome variables included the average holding force 0.2 seconds following force profile commencement and 0.2 seconds prior to the termination of the holding phase (d), the standard deviation of the holding forces between the five trials completed by the participants (between-trial variability), splitting force (c), and splitting duration (e). (**C**) Superimposition at splitting force of the splitting phase of two trials conducted by the same participant. A step-wise increase in force highlighted by the black arrows can be observed in the inferior force profile, but not in the superior force profile. Measurement of the frequency of trials exhibiting a step-wise force ramp-increase during the splitting phase was performed for all participants.

Study IV

This study involved measurement of jaw kinematics and jaw muscle activity. As shown in Figure 4A, a specially designed device (Umeå University, Physiology Section, IMB, Umeå, Sweden) was employed to record how the mandible moved in relation to the maxilla in the 3D space [20]. The device was made of a lightweight frame positioned on the nose bridge of the participant and tied to the head with Velcro straps that could be adjusted, similar to spectacles. The frame had two extending arms consisting of four magnetic sensors on each side, capable of 0.1-mm precision and 0-100 Hz bandwidth. The sensors kept track of the movement of a 10x5x5-mm permanent magnet placed underneath the chin of the participant with Leukoplast®

adhesive tape. A specially designed electromyographic (EMG) device was used to measure the masseter muscle activity on both sides. This device comprised two bipolar electrodes with a diameter of 2 mm, 6Hz-2.5kHz bandwidth, and a distance between them of 12 mm (Umeå University, Physiology Section, IMB, Umeå, Sweden). Prior to applying the electrodes, alcohol was used to clean the skin and the electrode surface was coated with conductive gel. A double-sided tape was subsequently employed to place the electrodes on the skin of the participant.

To ensure that the rheological properties of food did not vary, standardised viscoelastic test food models were created in the laboratory (Figure 4B) [20, 37]. Thus, the models were identical in size (10x20 mm) and rheological properties but one type was soft (yellow) and the other was hard (green). Three test food models of each type were given to the participants to eat in a semi-random order. Prior to the experiment, the participants were required to establish the chewing side they preferred and use solely that side during the experiment. The participants had to hold out their tongue so that the test food models could be placed there by the main researcher in a pre-established sequence. The participants subsequently closed their teeth into intercuspation and kept the food models between the tongue and palate for 2-4 seconds before chewing and swallowing. Task completion was followed by closure of teeth into intercuspation. During trial interim, the participants were allowed different activities, including relaxing, drinking, speaking, and mouth rinsing.

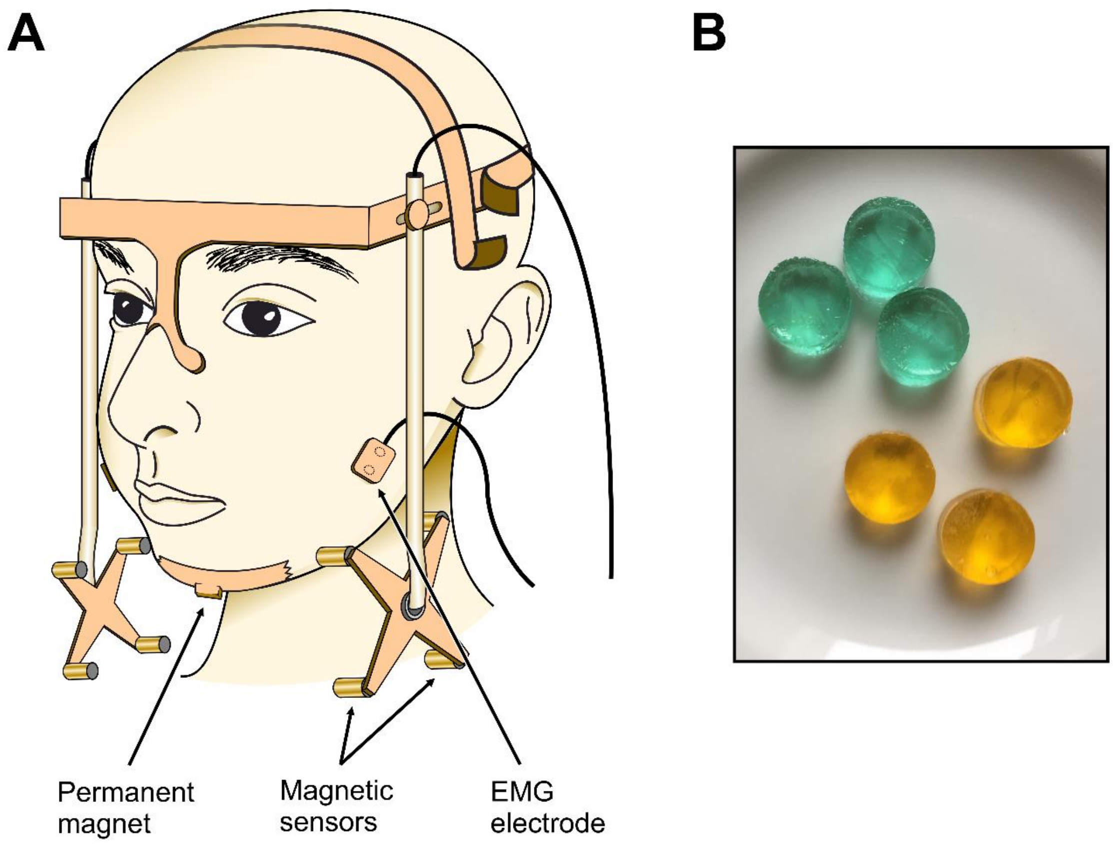


Figure 4. (**A**) Schematic representation of the specially designed magnetic jaw tracking apparatus and the bipolar surface EMG apparatus. **(B)** The participants were given three soft (yellow) and three hard (green) viscoelastic test food models to eat during measurement of the jaw kinematics and EMG activity of the bilateral masseter muscle.

2.5 DATA ANALYSIS

The WinSC/WinZoom software (Physiology Section, IMB, Umeå University, Umeå, Sweden) was employed for recording and analysing the data derived from *Studies II-IV*. The sampling of the force signals from *Studies II and III* was done at 1 kHz, while low-passed filtering was applied at 250 Hz. Meanwhile, the sampling of the jaw kinematic recordings and the EMG recordings from *Studies IV* was respectively done at 800 Hz and 3.2 kHz. The processing of the EMG data was performed as a root-mean-square (RMS) with a ±31-millisecond window.

Study II

As shown in Figure 2C, during the oral force control task, the whole force profile of 6-7 seconds was separated into an initial time-segment, which was equivalent to the first two seconds of the force profile and defined by rapid force overshoot, and a latter time-segment, which was equivalent to the rest of the 4-5 seconds and defined by greater stability. In the initial segment, the peak force was the outcome variable, while in the latter segment, the average force (holding force) and coefficient of variation (force variability) were the outcome variables.

Study III

Previous research has provided a comprehensive discussion of the hold-and-split force profile (Trulsson & Johansson, 1996a; Trulsson & Gunne, 1998; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009, 2011; Kumar *et al.*, 2014, 2015). As shown in Figure 3B, in this work, the whole temporal force profile was separated into two phases, namely, the food holding and splitting phases. The former was defined by a low and steady force profile beginning after the initial contact with the food (a) and lasting for 3-4 seconds prior to the initialisation of the splitting phase (b). The latter commenced when the force rate exceeded 5 N/s and was defined by a quick force ramp-increase resulting in the food being split (c). Measurements were performed of the average holding force 0.2 seconds after force profile commencement and 0.2 seconds prior to holding phase termination (d), as well as of the standard deviation among the trials undertaken by the same participant (between-trial variability). Moreover, the splitting force (c) and the interval between the splitting phase commencement and peak splitting force (e) were also measured during the splitting phase (splitting duration). Trials exhibiting a step-wise force ramp-increase were identified by examining the force ramp-increase pattern from the splitting phase (Figure 3C). In general, such trials are defined by force degeneration in two or more phases and subsequent rise in compensatory force, resulting in the food being split.

Study IV

As illustrated in Figure 5A, every chewing sequence associated with eating of the different test food models was broken down into a beginning, middle, and end segments, each of which comprised three sequential chewing cycles. In turn, every chewing cycle consisted of opening, closing, and occlusal phases. The opening phase began with the vertical opening of the mandible at least 1 mm from the intercuspation of the teeth and ended with the maximum opening of the mandible (Figure 5B). The closing phase began with mandible reversal from the maximum vertical opening to the initial vertical position of opening phase commencement. The occlusal phase began when the closing phase ended and continued until the subsequent opening phase. Since the EMG signals among participants varied with time, normalisation of the signals in every phase was undertaken without distorting the phase-related temporal data by dividing the signals by the average EMG activity attained in the entirety of the chewing cycles pertaining to every participant. The number of chewing cycles, chewing sequence duration, chewing rate, lateral and vertical jaw movement amplitude, velocity of jaw opening and closing, jaw opening, closing, and occlusal duration, as well as the normalised EMG activity associated with the jaw closing and occlusal phases were the outcome variables chosen from the data related to jaw kinematics and jaw muscle activity.

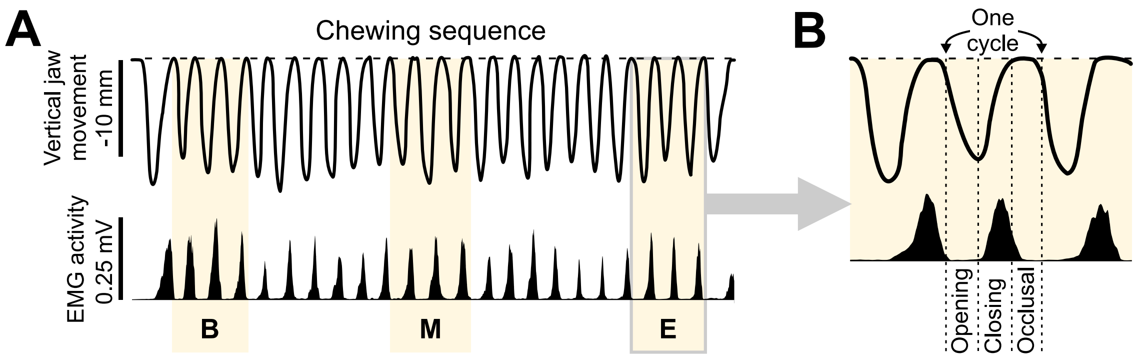


Figure 5. (A) The vertical jaw movement and processed EMG signal in one chewing sequence. The chewing sequence had a beginning (B), middle (M), and end (E) segment, which in turn comprised three sequential chewing cycles. **(B)** Enlarged perspective of the three chewing cycles, each of which comprised an opening, closing, and occlusal phase.

2.6 STATISTICS

In the case of *Study I*, a “meta-like” approach was attempted, with integration of the results derived from the reviewed studies related to each chewing parameter. The Statistica software version 13 (TIBCO Software Inc., 2018) was used for the purposes of statistical analysis of *Studies II-IV*, while the Shapiro-Wilk test and Q-Q and histogram plots were used to assess the normality assumption regarding the outcome variables in *Studies II and III*. In every statistical test, significance was deemed to be indicated by a *p* value of less than 0.05

Study II

After calculation of the mean of the three trials for the three outcome variables of peak force, holding force, and force variability, a number of models of repeated measure analysis of variance (ANOVA) were applied. In these models, the factors employed were the two-level load conditions (i.e. sequential and non-sequential) and the four-level load masses (i.e. 50, 100, 200, and 300 gm). Furthermore, the categorical factor was denoted by the six-level age groups. Tukey’s Honest Significant Difference test was the post-hoc test that was conducted when a major effect/interaction was discovered. Moreover, *SegReg* software (Oosterbaan, 2019) was used to undertake segmented regression analysis of the age-related trends in relation to the above outcome variables. An average of the three trials of every outcome variable was produced and the trials were also ordered according to increasing age and subjected to linear segmented regression. The software was capable of automatic detection of the sudden change (breakpoint) in the linear relationship between the outcome variables and age, with a confidence interval of 90%.

Study III

Calculation of the average of the five trials performed by every participant was undertaken for all the outcome variables during the phases of food holding and splitting. Furthermore, calculation of the frequency of trials exhibiting a step-wise force ramp-increase during food splitting was undertaken for every participant. All the outcome variables were assessed among the six dental age groups via one-way ANOVA. Dunnett post-hoc test was conducted on the key results to find out how the groups of children differed from the adult group.

Study IV

Non-parametric tests were carried out on the chosen outcome variables associated with jaw kinematics and jaw muscle activity during the beginning, middle, and end segments of chewing. The Kruskal-Wallis H test was conducted based on a Dunn-Bonferroni adjusted pairwise comparison to examine discrepancies associated with age for the chosen variables during the three segments in food of varying hardness. Meanwhile, Friedman ANOVA and Kendall Coefficient of Concordance test were performed to determine discrepancies in every variable as chewing progressed through the different segments of the sequence in every age group. Moreover, since the beginning of the chewing sequence is generally associated with adaptation to food hardness, as proven earlier (Grigoriadis *et al.*, 2011), the Wilcoxon Matched Pairs test was conducted to assess how adaptable the chosen variables were to food hardness at the beginning of the chewing sequence for every age group.

3 RESULTS

3.1 STUDY I

Of the total of 6193 studies identified through the search process, 53 were eventually chosen for inclusion (Figure 6). The quality of most of the chosen studies was judged to be moderate-to-low, but nine of the studies had high-to-moderate quality (Ingervall & Thilander, 1974; Fields *et al.*, 1986; Julien *et al.*, 1996; Gisel, 2008; Yamanaka *et al.*, 2009; Varga *et al.*, 2011; Owais *et al.*, 2013; Scudine *et al.*, 2016; Kaya *et al.*, 2017). The four key objective parameters of chewing were examined in all the chosen studies, with multiple parameters being addressed in a few studies. In the following part, an overview is provided regarding the transformations undergone by these parameters in relation to age.

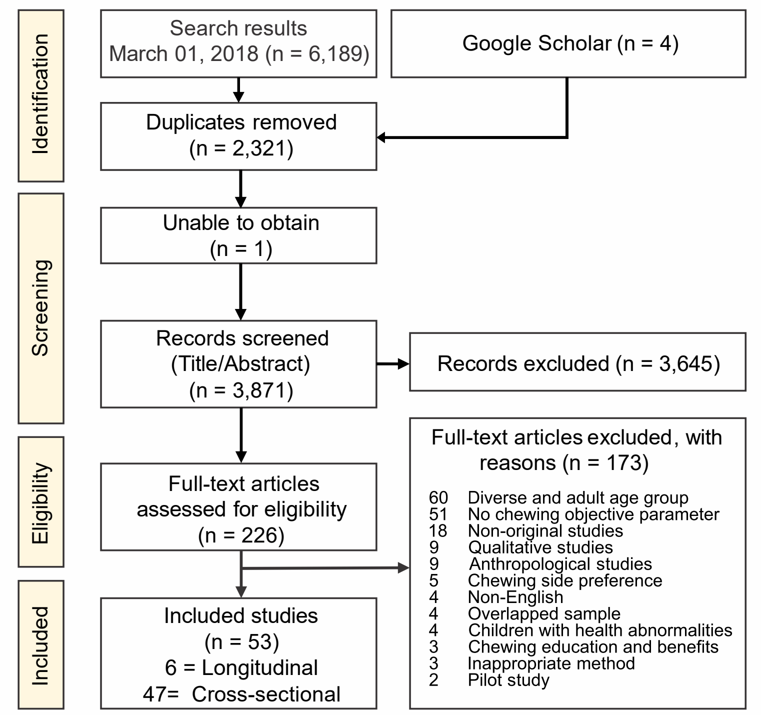


Figure 6. PRISMA flow diagram showing the process of screening the database search result and the selection of the studies satisfying the eligibility criteria.

3.1.1 Maximum occlusal bite force

MOBF measurement in healthy children with or without adults was undertaken in 21 studies (Linderholm *et al.*, 1971; Fields *et al.*, 1986; Bakke *et al.*, 1990; Braun *et al.*, 1996; Julien *et al.*, 1996; Maki *et al.*, 2001; Karibe *et al.*, 2003; Matsubara *et al.*, 2006; Gavião *et al.*, 2007; Oueis, 2009; Yamanaka *et al.*, 2009; Palinkas *et al.*, 2010; Castelo, Pereira, *et al.*, 2010; Sato & Yoshiike, 2011; Varga *et al.*, 2011; Ohira *et al.*, 2012; Owais *et al.*, 2013; Takaki *et al.*, 2014; Scudine *et al.*, 2016; Pedroni-Pereira *et al.*, 2017; Hama *et al.*, 2017), but they differed in terms of the devices employed to gauge force and the positioning of the devices in the mouth. Figure 7 shows the MOBF trend lines associated with age and sex that were derived from the reviewed studies. According to the empirical examination of those trend lines, age 3 was associated with minimal MOBF. However, the MOBF increased gradually with age, beginning to show sex-differences at age 10, which became more pronounced during puberty and after puberty, when adult-like forces were achieved.

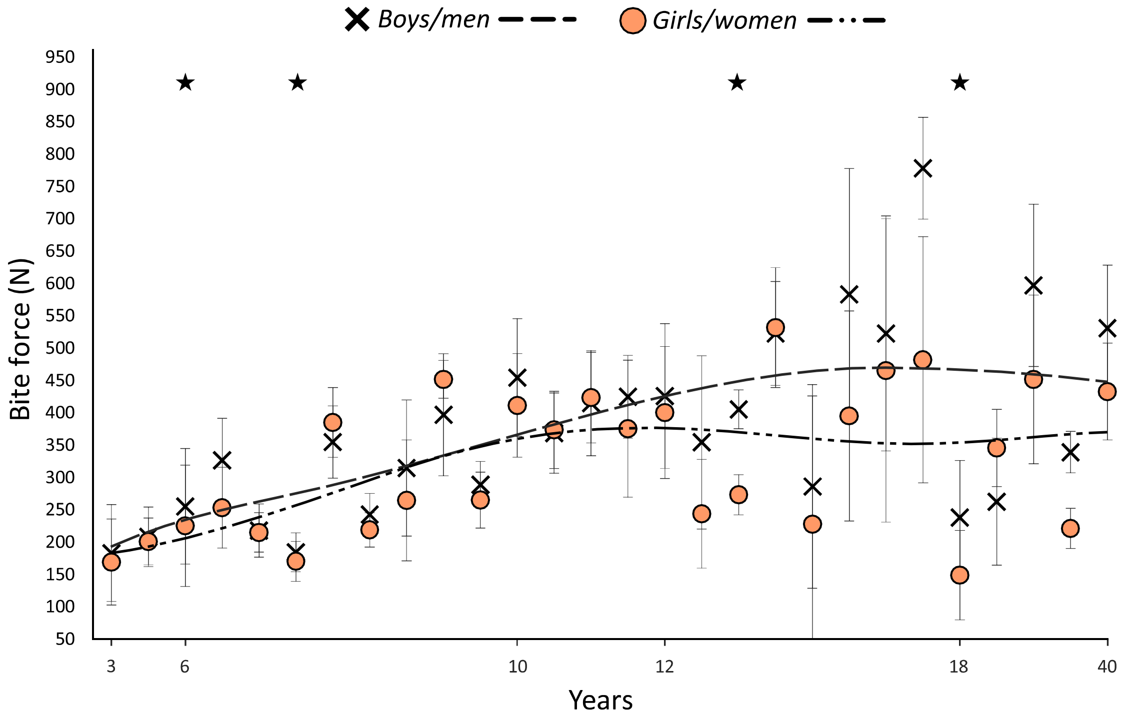


Figure 7. The MOBF pooled mean (SD) trend lines associated with age and sex in male and female individuals between 3 and 40 years of age, as derived from the reviewed studies. A star symbol (★) was allocated to values overlapping between two age groups.

3.1.2 Chewing electromyography

Measurement of the EMG activity during regular chewing activity in healthy children was undertaken in nine studies (Ingervall & Thilander, 1974; Ingervall, 1978; Pancherz, 1980; Ogura *et al.*, 1987; Takada *et al.*, 1994; Green *et al.*, 1997; Steeve *et al.*, 2008; Palinkas *et al.*, 2013; Simione *et al.*, 2018). Comparable to the studies that measured MOBF, a range of EMG devices and processing techniques were employed by these studies to analyse EMG signals. According to the findings, unlike in older children and adults, greater variation was exhibited by the EMG activity in children aged nine months. However, such variation diminished and greater synchronisation was displayed by masticatory muscle EMG activity between the ages of one and two years old. Furthermore, a close correlation was reported between elevated EMG activity, reduced chewing duration and chewing cycles of the masseter muscle, on the one hand, and the increase in the number of pairs of tooth occlusion, on the other hand. Additionally, in children aged 11, a correlation existed between food hardness and elevated EMG activity as well. At around the same age that the trend lines of MOBF began to show alterations associated with age (Figure 7), a marked rise in EMG activity was recorded at about 13 years of age, which started to resemble adult EMG activity.

3.1.3 Chewing-related jaw kinematics

Measurement of jaw kinematics, including chewing duration and cycles, and jaw movement pattern and length, in healthy children was undertaken in 22 studies (Wickwire *et al.*, 1981; Gibbs *et al.*, 1982; Schwartz *et al.*, 1984; Schwaab *et al.*, 1986; Gisel, 1988, 2008; Archambault *et al.*, 1991; Kiliaridis *et al.*, 1991; Takada *et al.*, 1994; Snipes *et al.*, 1998; Papargyriou *et al.*, 2000; Yashiro *et al.*, 2003; Hayasaki *et al.*, 2003; Saitoh *et al.*, 2010, 2004; Wilson & Green, 2009; Steeve, 2010; Kubota *et al.*, 2010; Wilson *et al.*, 2012; Yamada-Ito *et al.*, 2013; Gerstner *et al.*, 2014; Utsumi *et al.*, 2015). It was found that, at nine months of age, the jaw movement pattern was undistinguishable, but this pattern was wider and shorter in older children compared to adults during chewing. Furthermore, as food hardness increased, so did chewing times and cycles as well as jaw movement length in healthy children (Figure 8). Chewing cycles also varied more significantly between individuals among children of 4-6 years of age than in adults. Meanwhile, the studies were inconsistent regarding whether the number of chewing cycles and jaw movement length decreased or increased in relation to age. The studies highlighted sex-related differences, with eating speed in children younger than eight years of age being higher in boys than in girls, whilst the opposite was true in individuals older than eight years of age. Adult-like chewing times, inter-individual chewing cycle variation, and jaw movement pattern were developed by 12-14 years of age.

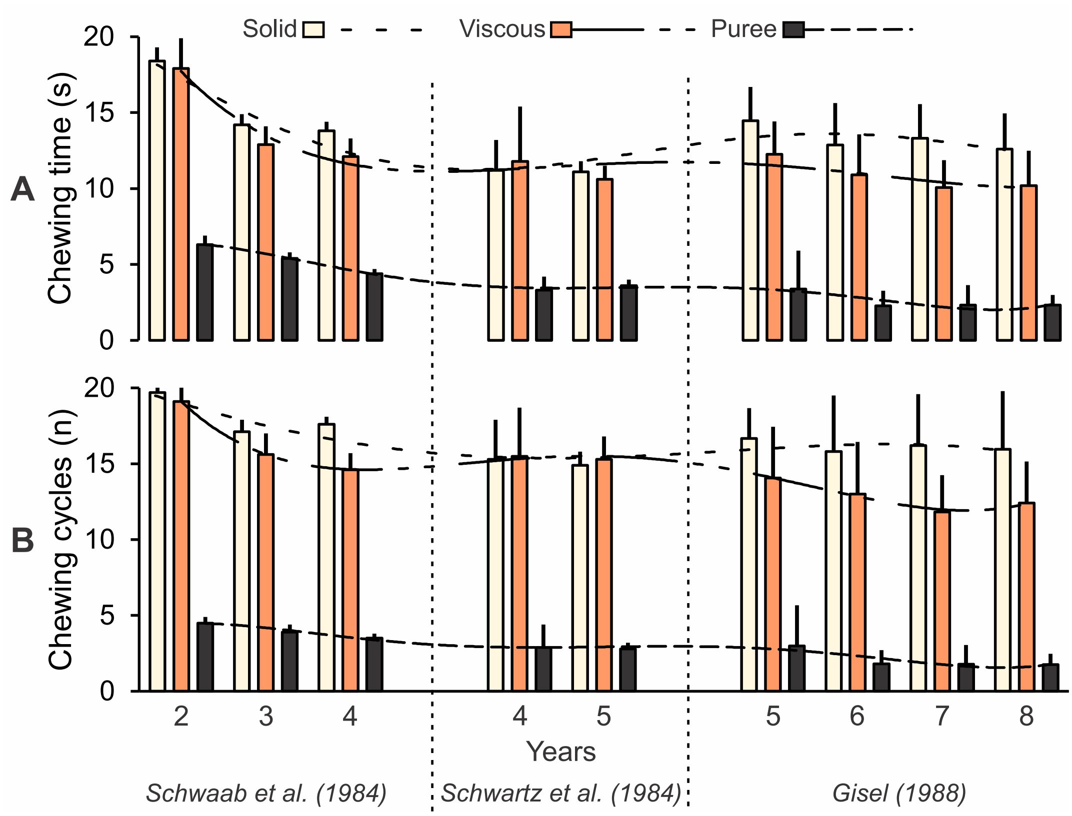


Figure 8. Findings from three studies employing identical test food and methods (Schwartz *et al.*, 1984; Schwaab *et al.*, 1986; Gisel, 1988) regarding chewing time (**A**) and number of chewing cycles (**B**) associated with children in the age range 2-8 years old eating food of different hardness (solid, viscous, puree).

3.1.4 Chewing efficiency

Food trituration and mixing ability of colour-changeable gums were the approaches used by 11 studies to examine chewing efficiency in healthy children (Julien *et al.*, 1996; Maki *et al.*, 2001; Matsubara *et al.*, 2006; Gavião *et al.*, 2007; Oueis, 2009; Ohira *et al.*, 2012; Scudine *et al.*, 2016; Ichikawa *et al.*, 2016; Hama *et al.*, 2017; Kaya *et al.*, 2017; Pedroni-Pereira *et al.*, 2017). A range of methods and food models were employed, just like with other parameters. Compared to children with mixed dentition, children with primary dentition had not only lower chewing efficiency, with test food fragmentation into bigger pieces, but also diminished mixing ability of colour-changeable gums. On the other hand, compared to adults, food trituration generated larger food particles in both child groups. A positive correlation was established between a higher number of pairs of tooth occlusion and ability to better fragment food and achieve colour-changeable gum mixing. At age 9, chewing efficiency began to display sex-related differences, with food trituration and mixing ability of colour-changeable gums being better in boys compared to girls.

3.2 STUDY II

3.2.1 Peak force, holding force and force variability

The peak force ($F_{5, 72} = 2.389$, $p = .046$) was markedly impacted by age, but the holding force ($F_{5, 72} = 1.567$, $p = .1803$) and force variability ($F_{5, 72} = 1.4393$, $p = .2207$) were not. Children with early-mixed dentition displayed a lower peak force than children with late-mixed dentition, according to the post-hoc test results ($p = .018$). Meanwhile, load condition did not substantially affect any of the three outcome variables (i.e. peak force, holding force, and force variability), but the load mass did have a notable effect (peak force: $F_{3, 216} = 52.43$, $p < .001$; holding force: $F_{3, 216} = 111.34$, $p < .001$; force variability: $F_{3, 216} = 37.762$, $p < .001$). As the load magnitude increased, the peak force and the holding force increased as well, whereas the force variability decreased (Figure 9).

3.2.2 Segmented regression analysis

Segmented regression analysis (see the section on Data Analysis) was applied to assess the developmental trends associated with the three outcome variables. Comparison with adults did not reveal any marked differences in the outcome variables (Figure 9), but a breakpoint of the linear relationship was discerned in all outcome variables for the conditions and load masses taken together (Figure 10). On the whole, late-mixed dentition was associated with the breakpoint of the trend lines associated with the peak and holding forces, while early-permanent dentition was associated with a more protracted breakpoint of the force variability trend line.

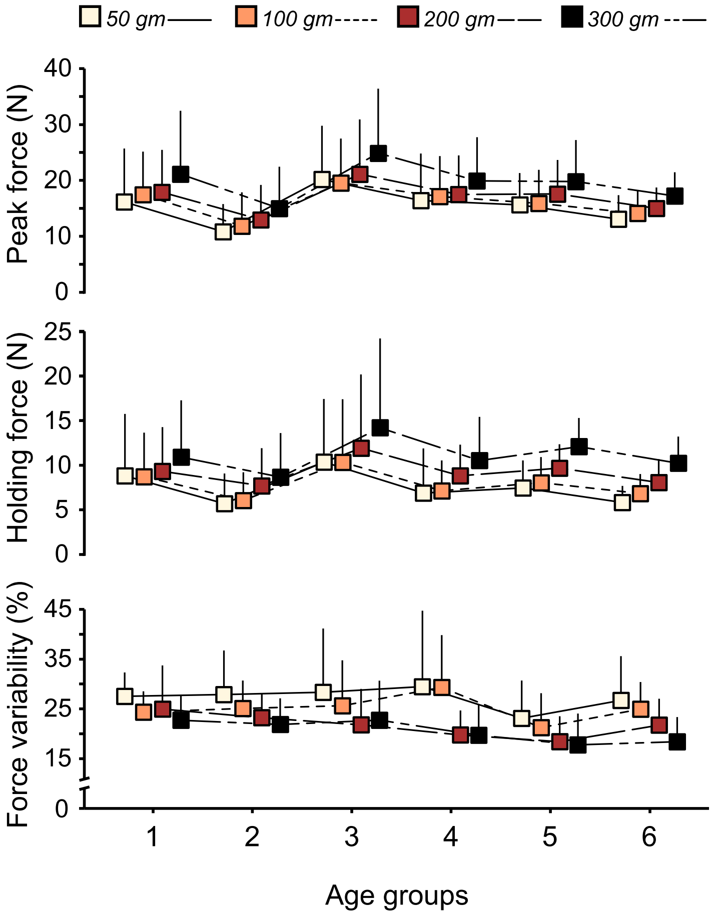


Figure 9. The mean and SD associated with the peak force, holding force and force variability for the four load masses pooled across the two load conditions from the six dental age groups; (1) primary dentition; (2) early-mixed dentition; (3) late-mixed dentition; (4) early-permanent dentition; (5) late-permanent dentition; (6) adults.

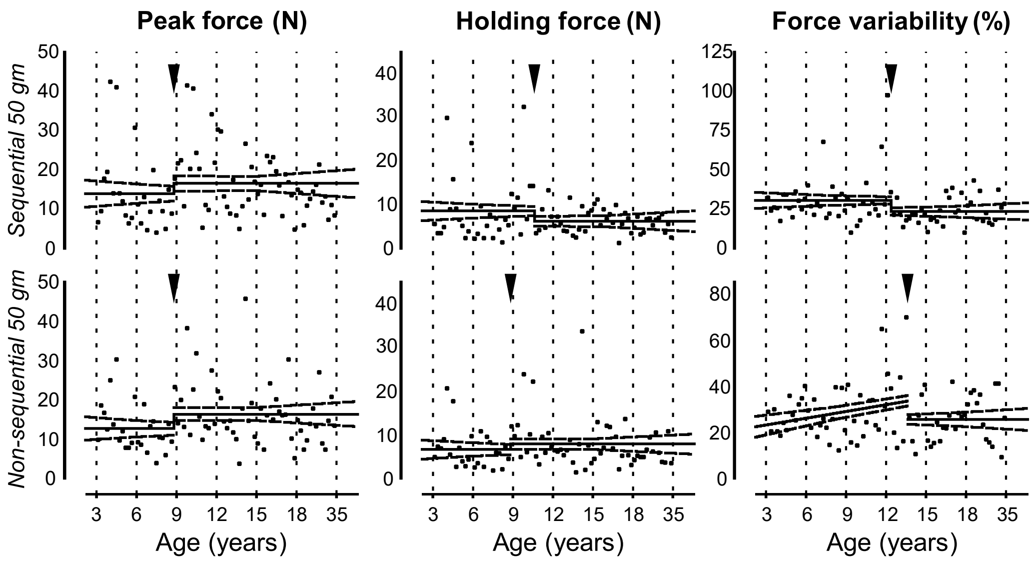


Figure 10. Trend analysis exemplification with segmented regression of the peak force, holding force and force variability during pulling and holding of 50-gm load under the two load conditions. The linear trend line breakpoint in the outcome variables is indicated by the black arrows. In the case of peak force and holding force, this breakpoint happened during late-mixed dentition, while in the case of force variability it occurred during early-permanent dentition. For a detailed analysis for all the loads and load conditions, please refer to figures 3 and 4 in (Almotairy et al., 2020).

3.3 STUDY III

3.3.1 Food holding

The primary dentition group was associated with maximum holding force (3.38 ± 1.62 N) and between-trial force variability (0.26 ± 0.07 N) in the context of food manipulation. The increase in age caused a decline in these two outcome variables, with the adult group having minimal holding force (0.84 ± 0.24 N) and force variability (1.38 ± 0.78 N). Aside for the late-permanent dentition group, all the groups of children displayed holding force and between-trial force variability of statistical significance compared to adults ($p < .05$) (Figure 11A and B).

3.3.2 Food splitting

Although the food splitting forces generally exceeded the holding forces, they were the same among the age groups. By contrast, solely the primary dentition ($p = .00023$) and early-mixed dentition groups ($p = .016$) exhibited markedly higher splitting durations whilst also showing statistical significance in terms of the frequency of step-wise force ramp-increase during the splitting phase ($p = .00035$ and $p = .015$, respectively) compared to adults (Figure 11C and D).

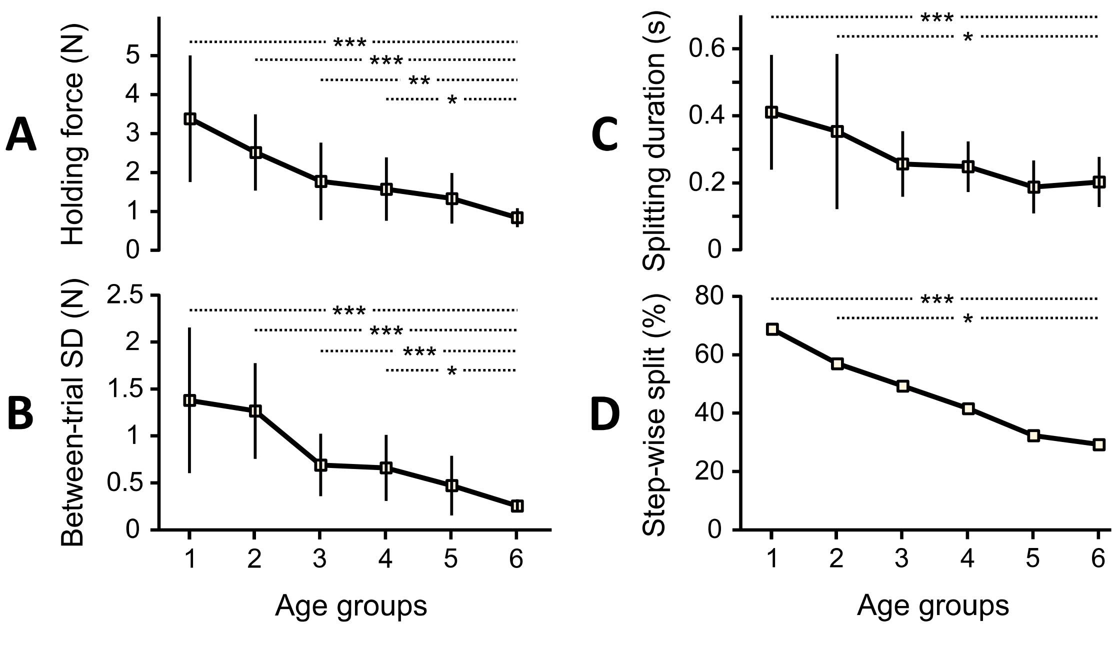


Figure 11. The mean (SD) associated with the food holding force (**A**), between-trial variability (**B**), and splitting duration (**C**) in the dental age groups. (**D**) The frequency of the step-wise force ramp-increase during the splitting phase in the different groups. (1) primary dentition; (2) early-mixed dentition; (3) late-mixed dentition; (4) early-permanent dentition; (5) late-permanent dentition; (6) adults. The star symbols *, **, and *** denote a *p*-value below 0.05, 0.01 and 0.001, respectively.

3.4 STUDY IV

3.4.1 Chewing sequence

The groups of children did not differ from the adults regarding the number of chewing cycles and chewing sequence duration, irrespective of food hardness (Figure 12A and B). A higher number of chewing cycles in relation to hard food compared to soft food was displayed solely by the primary dentition and adults groups ($p < .01$). In terms of chewing sequence duration, it did not differ much according to food hardness in any of the groups of children, but it did differ among the adults, who displayed a lengthier chewing sequence duration in association with hard food compared to soft food ($p = .009$).

3.4.2 Chewing cycle duration

In the context of eating hard food, the primary dentition group displayed shorter jaw opening duration of the chewing cycle (Figure 13A) at the chewing sequence beginning ($p = .0149$) and end ($p = .0099$) compared to adults. On the other hand, the groups of children did not differ from the adults in terms of jaw closing and occlusal duration, irrespective of food hardness (Figure 13B). The primary dentition group was the only one of the other age groups with a jaw opening duration that was shorter when eating hard than soft food ($p = .037$). Furthermore, the primary dentition group ($p = .0012$) and early-mixed dentition group ($p = .0218$) displayed shorter occlusal duration as well when eating hard food compared to soft food. As the chewing sequence progressed, there was a lengthening of the occlusal duration in relation to hard food consumption in the primary dentition group ($p = .0075$), early-mixed dentition group ($p = .0451$), and late-mixed dentition group ($p = .0075$).

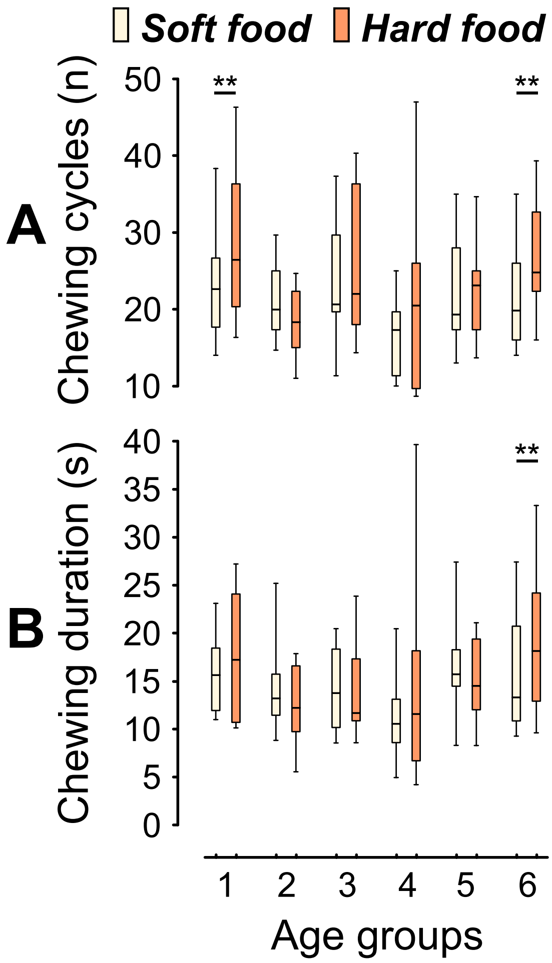


Figure 12. The median (interquartile range) of the age groups for the number of chewing cycles (**A**) and chewing sequence duration (**B**). (1) primary dentition; (2) early-mixed dentition; (3) late-mixed dentition; (4) early-permanent dentition; (5) late-permanent dentition; (6) adults. The star symbols *, **, and *** denote a *p*-value below 0.05, 0.01 and 0.001, respectively.

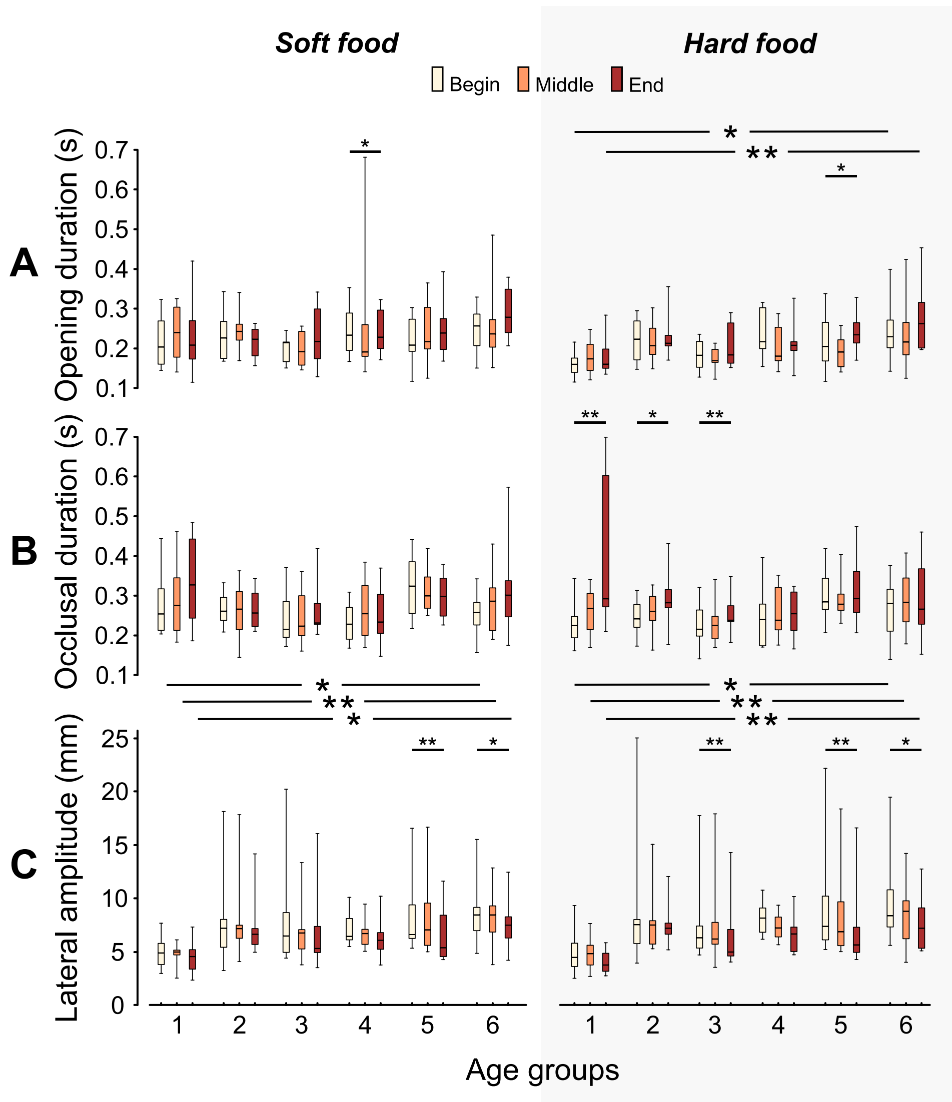


Figure 13. The median (interquartile range) of the age groups for the jaw opening (**A**) and occlusal (**B**) duration and the jaw lateral amplitude (**C**). (1) primary dentition; (2) early-mixed dentition; (3) late-mixed dentition; (4) early-permanent dentition; (5) late-permanent dentition; (6) adults. The star symbols *, **, and *** denote a *p*-value below 0.05, 0.01 and 0.001, respectively.

3.4.3 Jaw kinematics

There were no differences between groups of children and adults in terms of the vertical jaw amplitude and the velocity of jaw opening and closing. Nevertheless, compared to the adult group, the primary dentition group had a shorter lateral jaw amplitude all through the chewing sequence, regardless of food hardness ($p < .05$) (Figure 13C).

Although none of the groups differed in terms of vertical and lateral jaw amplitude for hard and soft food, the velocity of jaw opening and closing during the eating of hard food was faster in the late-permanent dentition and adult groups than during the eating of soft food ($p < .03$). Likewise, the velocity of jaw opening in the primary dentition group and the velocity of jaw closing in the early-mixed dentition group was faster during the eating of hard food than during the eating of soft food ($p = .0218$ and $p = .007$, respectively).

As the chewing sequence progressed, the velocity of jaw opening reduced, regardless of food hardness, in every age groups ($p < .05$), except the primary dentition group, where the velocity of jaw opening remained unchanged as the chewing sequence progressed through its three segments solely during the eating of soft food. On the other hand, chewing caused a reduction in vertical jaw amplitude and velocity of jaw closing in every age groups, regardless of food hardness ($p < .05$). Furthermore, for both hard and soft food, the lateral jaw amplitude declined in the late-permanent dentition group and the adult group as the chewing sequence progressed ($p < .05$). By contrast, the lateral jaw amplitude declined in the late-mixed dentition group solely during the chewing of hard food ($p = .0075$).

3.4.4 Jaw muscle activity

Compared to the adult group, the primary dentition group exhibited higher EMG activity of the masseter muscle during jaw closing at the end of the chewing sequence, regardless of food hardness ($p = .002$ for soft food and $p = .025$ for hard food). The EMG activity differed only in the groups of late-permanent dentition and adults with regard to food hardness increase at the chewing sequence beginning (Figure 14A and B). However, as the chewing sequence progressed, there was a reduction in EMG activity during the jaw closing and occlusal phases, irrespective of food hardness. The only exception was the primary dentition group, in which the EMG activity remained the same as the chewing sequence progressed.

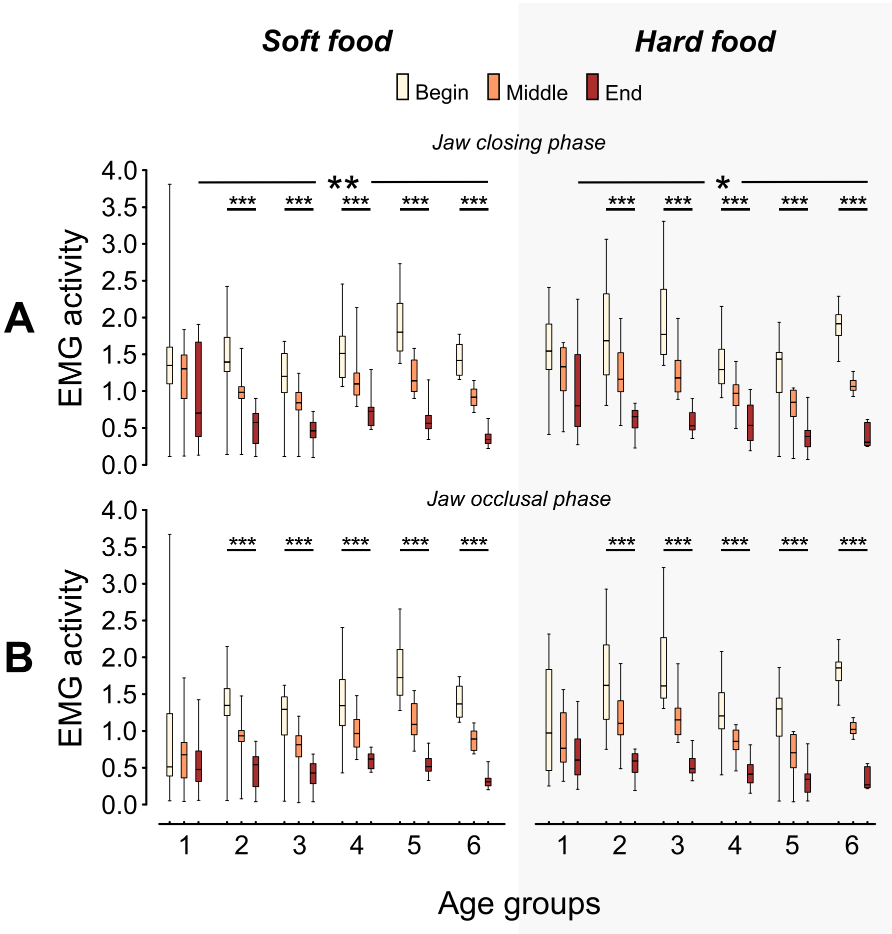
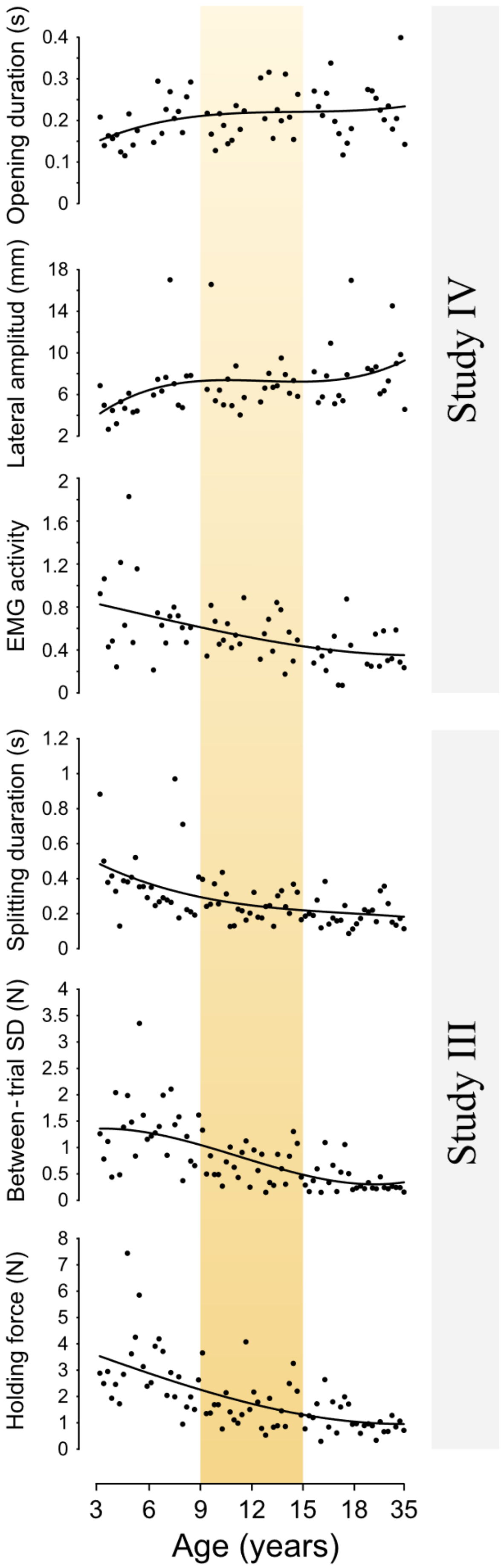


Figure 14. The median (interquartile range) of the age groups for the normalized masseter EMG activity during jaw closing (**A**) and occlusal (**B**) phases for soft and hard food models during the beginning (light yellow), middle (orange), and end (red) of the chewing sequence. (1) primary dentition; (2) early-mixed dentition; (3) late-mixed dentition; (4) early-permanent dentition; (5) late-permanent dentition; (6) adults. The star symbols *, **, and *** denote a p-value below 0.05, 0.01 and 0.001, respectively.

4 GENERAL DISCUSSION

A number of studies have sought to shed light on how various physiological behaviours (e.g. finger precision grip, speaking) developed in children (Forssberg *et al.*, 1991, 1992, 1995; Gordon *et al.*, 1992; Eliasson *et al.*, 1995; Green *et al.*, 2002; Walsh & Smith, 2002). With regard to chewing and biting behaviours, earlier research provided evidence that children and adults differed (Almotairy *et al.*, 2018), yet the age-related changes undergone by these behaviours during the transition from children to adults remain unknown (*Study I*) (Almotairy *et al.*, 2018). Hence, the purpose of the present work was to explore how the oral sensorimotor control changed with age vis-à-vis unpredictability in load changes (*Study II*) (Almotairy *et al.*, 2020), food biting manoeuvres (*Study III*) (Almotairy *et al.*, 2020) and chewing of food of varying hardness (*Study IV*) (Almotairy, Kumar, & Grigoriadis, 2020a). In terms of the efficiency of undertaking the unpredictable oral motor task, young children and adults did not differ (*Study II*), but age-related changes between the groups of children and adults were identified from the outcomes of food biting and chewing activities (*Studies III* and *IV*). For example, compared to adults, children in the age range 3-14 years displayed higher and more variable biting forces associated with the front teeth (*Study III*). Moreover, food splitting phase was lengthier and compensatory force ramp-increase higher in the groups of primary and early-mixed dentition (*Study III*). Meanwhile, there was unsuccessful adaptation of jaw kinematics and jaw muscle activity in children aged 3-14 years during chewing of food of increasing hardness (*Study IV*). Furthermore, the sensorimotor control displayed by the late-permanent dentition group during biting and chewing resembled the fully developed one of adults (*Studies II-IV*). On the whole, the findings of this work suggest that the transformations underwent by orofacial structures (i.e. skeletal, dental, and muscular structures) shape the manner in which the biting and chewing behaviours develop in healthy children. This is exemplified by the significant modifications affecting the variables investigated in *Studies III* and *IV*, during the ages of 9-14 years (late-mixed to early-permanent dentition), as reflected by the trend lines associated with those variables (Figure 15). Additionally, the trend lines were equivalent to the trend lines of maximal occlusal bite force (Figure 7) and of the unpredictable oral motor control task (Figure 10) in *Study I* and *Study II*, respectively.

The existing knowledge about the development of jaw motor control and chewing in healthy children was compiled by the systematic review (*Study I*). The review findings helped to distinguish the aspects requiring further research and formulate a hypothesis for the three other studies (*Studies II-IV*), which stated that the late-mixed to early-permanent dentition (10-14 years) was the period when most chewing parameters matured in healthy children. It was additionally hypothesised that the phases of tooth eruption had a significant impact on the transformations underwent by the examined chewing parameters. Nevertheless, owing to the inconsistencies among the reviewed studies regarding employed methods and test food models, the veracity of the hypothesis that adult-like behaviour is achieved during late-mixed and early-permanent dentition cannot be confirmed. An earlier study indicated that chewing behaviour could be affected by discrepancies in the textural qualities of food, including size, hardness, and elasticity (Woda *et al.*, 2006). Hence, those qualities must be controlled to avoid food-related ambiguities in chewing studies (Lassauzay *et al.*, 2000; Peyron *et al.*, 2002). Furthermore, inter-study comparative analysis of a particular chewing parameter (e.g. EMG signals) may not be possible in the absence of standardisation of normalisation protocol and



processing method. Masticatory muscle functional status can be derived from the MOBF (Bakke, 2006), but this is usually higher compared to chewing forces (Trulsson & Johansson, 1996a). The use of measurements like MOBF could also create vagueness in examinations of the sensorimotor development of biting and chewing in children. Factors such as the width of the bite force transducer and positioning in the mouth could affect MOBF, which means that this measurement presents sensitivity to the applied method (Fields *et al.*, 1986). What is more, the real status of the CNS may not be reliably indicated by MOBF because this measurement depends significantly on the muscular mechanical capacity (e.g. muscle size and power) of each individual (Bakke *et al.*, 1990; Throckmorton & Dean, 1994). Consequently, care was taken to address such potential sources of ambiguity in *Studies II-IV* by employing tasks that were not functionally demanding, creating standardised food models with controlled textural qualities, and adopting standardised techniques and data processing approaches to enable comparative analysis of the data among the groups of children and adults.

Figure 15. The age-related trend (black) lines of the chosen outcome variables derived from Study III and IV. Each black dot represents an individual participant (78 participants for Study III and 50 participants for Study IV) ordered according to increasing age. Yellow gradient colour running across the figure highlights the late-mixed and early-permanent dentition stages.

4.1 ORAL MOTOR CONTROL STRATEGIES DURING UNPREDICTABLE LOAD DEMANDS (STUDY II)

4.1.1 The oral motor control in relation to load changes

The increase in load mass caused an increase in biting and holding forces in both children and adults (Study II), which may suggest that the force output of the oral motor system is correlated to load requirements. According to Henneman's size principle, the recruitment of the motor neurons in a single muscle occurred in an orderly manner, beginning with firing smaller motor neurons and subsequently larger ones, until the functional demand was fulfilled by the produced force output (Henneman *et al.*, 1965). Such correlation of force output to the functional demand is believed to enhance the force control in the motor system, thus reducing the likelihood of muscular fatigue (Van Eijden & Turkawski, 2001). As implied by the results, both the children and adults employed sufficient force output in an economical fashion with regard to load requirement. A recent study indicated that children with primary dentition had an average maximum incisor bite force of 150 N, while children with late-permanent dentition displayed a force of 244 N (Manns *et al.*, 2020). By contrast, this study found that, at a load mass of 300 gm, children with primary and late-permanent dentition respectively achieved just 13% and 8% of the maximum incisor bite force measured earlier, which was equivalent to around 20 N. Therefore, by comparison to the maximum biting task in the first study, the functional capacity of young children's masticatory muscles was not challenged by the load masses. As shown in Figure 7, young children have a more reduced functional capacity than older children and adults, which determined the extreme forces produced by the masticatory muscles in the maximum biting task and produced biting force discrepancies associated with age. Hence, contrary to earlier assumptions, it is not so much CNS alterations causing age-related discrepancies in the maximum biting force, but age-related discrepancies in muscle mass and power instead.

Research that investigated how hand motor control developed reported that children without health problem exhibited greater movement variation during unpredictable load changes than adults (Schneiberg *et al.*, 2002; Contreras-Vidal, 2006; King *et al.*, 2012). By contrast, the second study in this work found that children and adults did not differ in terms of force variability. According to earlier studies, an inverse correlation exists in the force variability in motor command and the force output magnitude (Laidlaw *et al.*, 2000; Hamilton *et al.*, 2004; Kumar, Tanaka, *et al.*, 2017; Almotairy, Kumar, & Grigoriadis, 2020b). Lower force output is associated with activation of a reduced number of motor neurons, which could potentially increase force variability (Hamilton *et al.*, 2004). Such observations are consistent with the findings of this work, which revealed that force variability was higher in both children and adults when the force output was lower than when it was higher.

As discussed in the introduction part, childhood is a period associated with ongoing transformations in the orofacial structures, but such transformations do not appear to significantly affect how the current oral motor task develops. This work is inconsistent with earlier research on hand motor control (Forssberg *et al.*, 1991, 1992; Schneiberg *et al.*, 2002; Contreras-Vidal, 2006; King *et al.*, 2012), as it observed that oral sensorimotor control was insignificantly impacted by load unpredictability. A number of discrepancies in methods and behaviour between this work and earlier research on hand motor control could explain the dissonance in results. Evidence has been produced that motor task development depends on how complex the task is (Kurgansky, 2014). This has led to the idea that children without health problems could accomplish adult-like motor control of tasks of low complexity quicker than tasks of greater complexity (Pellizzer & Hauert, 1996; Smyth *et al.*, 2004; Pantes *et al.*, 2009). Hence, it is contended that motor control changes related to age were not revealed in the present work because the employed task was insufficiently demanding. This notion is bolstered by the fact that the muscular biomechanical capacity of children in hand motor control studies was challenged by the heavy load masses that were used (Forssberg *et al.*, 1991, 1992; Gordon *et al.*, 1992). The reason for using lighter load masses in the present work was to ensure that the adults did not have a biomechanical advantage over the children. Nevertheless, it is argued that age-related changes are more apparent when heavier rather than lighter load masses are employed owing not to CNS alterations, but to discrepancies in muscular biomechanics between children and adults. Dissimilarities in the degrees of freedom between the hand and oral motor systems could also be a reason. An earlier study observed that the higher degrees of freedom in a motor system increases its flexibility to execute the same motor task using multiple motor solutions (Kay, 1988). On the downside, the greater motor flexibility made learning, selection and fine-tuning of the best motor solution for a given task more difficult for the motor system (Bernstein, 1967; Braun *et al.*, 2009). Different from the hand motor system with multiple joints, the oral motor system has only bilaterally hinging joints, which may restrict its degrees of freedom and therefore its range of motor solutions. Consequently, it can be postulated that age-related changes may not be as obvious in the oral motor system and other motor systems with restricted degrees of freedom as in the hand motor system and other systems with higher degrees of freedom.

4.1.2 Trends of oral motor control development

The children and adults did not differ with regard to the performance of the oral motor task, but the alterations in the trend lines of oral motor control during late-mixed and early-permanent dentition revealed by the segmented regression analysis were consistent with the observations of *Study I*. Modifications in the primary/permanent front teeth and associated periodontium transformations (Maeda *et al.*, 1999; Shi *et al.*, 2006; Umemura *et al.*, 2010; Miki *et al.*, 2015) as well as completion of root formation of permanent teeth at 10-11 years (Nelson, 2014) could explain the trend line alterations.

4.2 SENSORIMOTOR CONTROL OF FOOD BITING MANEUVRES (STUDY III)

4.2.1 Regulation of forces during food manipulation

The hold-and-split task was more challenging than the oral motor control task in *Study II* because gentle holding of the peanut prior to splitting it necessitates a high level of skill. Consequently, the children and adults differed in the manner in which they manipulated the food. In *Study III*, there was consistency between the changes in the trend lines of segmented regression and the age-related changes of biting force in the context of food manipulation. Evidence from previous research suggested that periodontal mechanoreceptors had a substantial influence on force magnitude and trajectory specifications (Trulsson & Johansson, 1996a, 1996b; Trulsson & Gunne, 1998; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009, 2011). leading to the notion that low holding forces were generally used by adults with normal periodontium for optimisation of sensory information from the PMRs (Trulsson, 2006; Johnsen *et al.*, 2007). Key information regarding food properties is gathered by the PMRs during the initial contact between the teeth and food and it is employed for muscle activity modulation during food biting. Consistent with earlier research on healthy adults (Trulsson & Johansson, 1996a; Trulsson & Gunne, 1998; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009, 2011), the adult participants in this work displayed an average holding force of 0.8 N, confirming that the PMRs were more sensitive at forces of less than 1 N for the front teeth (Trulsson & Johansson, 1996b).

The holding force during food manipulation undergoes a 200-300% increase when the PMR-derived sensory information is inhibited by dental anaesthesia (Trulsson & Johansson, 1996a; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009; Grigoriadis *et al.*, 2011; Grigoriadis & Trulsson, 2018) and a 250-350% increase in cases of lack of sensory inputs, as happens with dental implants (Trulsson & Gunne, 1998; Svensson & Trulsson, 2011). The implication of such findings is that the motor system makes up for the deactivation of PMR-derived sensory information by increasing holding forces for food manipulation (Trulsson & Johansson, 1996a; Trulsson & Gunne, 1998; Johnsen *et al.*, 2007; Svensson & Trulsson, 2009, 2011). The present work notably discovered that the holding forces measured for the children were the same as the holding forces employed in cases of affected PMR signals. As shown in Figure 11A, the primary and early-mixed dentition groups displayed a 400% and a 300% increase in holding forces, respectively, whilst the late-mixed dentition and early-permanent dentition groups exhibited a 200% increase.

Compared to adults, greater force variation was demonstrated by the primary to early-permanent dentition groups, which is similar to the findings of other behavioural studies on healthy children (Hadders-Algra, 2002; Schneiberg *et al.*, 2002; van der Heide *et al.*, 2003; Dusing & Harbourne, 2010; Dusing, 2016). Such variation may reflect the fact that children's oral motor control is not as developed as that of adults. In healthy children, motor variation is actually critical for the motor system to develop adequately and hone the capacity of identifying motor solutions (Hadders-Algra, 2008; Helders, 2010; Herzfeld & Shadmehr, 2014). To address a particular motor task, young children extract and assimilate a suitable motor solution from a range of available ones. As orofacial structures (e.g. jaws, muscles, dentition) develop, children use the experience derived from development to improve their oral motor performance (Vereijken, 2010), which most likely occurs during the phase of late-permanent dentition (Figure 11B).

4.2.2 Regulation of forces during food splitting

The splitting force magnitude is not greatly dependent on the sensory input from the PMRs (Trulsson & Gunne, 1998; Johansson *et al.*, 2006; Svensson & Trulsson, 2009, 2011; Kumar, Castrillon, *et al.*, 2017), but on the mechanical properties of food and the incisal edge sharpness, as indicated by the fact that splitting forces do not differ with age (Trulsson & Johansson, 1996a; Svensson & Trulsson, 2009). On the other hand, food splitting duration depends significantly on the PMR sensory input (Johansson *et al.*, 2006; Svensson & Trulsson, 2009, 2011). The results of this work are consistent with those of earlier research reporting that food splitting was achieved by adults with normal periodontium in around 0.2 seconds (Trulsson & Gunne, 1998; Johansson *et al.*, 2006; Svensson & Trulsson, 2009, 2011). Meanwhile, the primary dentition and early-mixed dentition groups displayed a splitting duration that was nearly double that of adults (Figure 10C), similar to that of individuals subjected to dental anaesthesia or suffer from periodontal destruction (Johansson *et al.*, 2006; Svensson & Trulsson, 2009). Likewise, food splitting was associated with a step-wise force ramp-increase in around 60% of the trials undertaken by the primary dentition and early-mixed dentition groups, whereas just 30% of the trials undertaken by the adults showed such increase (Figure 10D). Such lengthier splitting duration and increased frequency of step-wise splitting phase may be considered compensatory mechanism to make up for the immature oral motor control in children.

4.3 DEVELOPMENT OF CHEWING BEHAVIOR IN CHILDREN (STUDY IV)

4.3.1 Age-related changes in chewing behavior

There is a lack of consistency in the existing evidence regarding the impact of age on the number of chewing cycles and chewing duration, with some studies indicating that children have reduced chewing cycles and chewing sequence duration compared to adults (Schwartz *et al.*, 1984; Schwaab *et al.*, 1986; Gisel, 1988, 2008; Archambault *et al.*, 1991; Wilson *et al.*, 2012; Simione *et al.*, 2018), whilst others report the opposite (Snipes *et al.*, 1998; Papargyriou *et al.*, 2000; Kubota *et al.*, 2010; Gerstner *et al.*, 2014). In the fourth study in this thesis, children and adults were not found to differ in terms of the number of chewing cycles and chewing sequence duration, and neither did they differ in terms of the vertical jaw amplitude. One explanation for this might be the size uniformity of the viscoelastic test food models, which led to the same amplitude of jaw opening in children and adults, and hence lack of difference in vertical jaw movements. On the other hand, the children and adults did differ with regard to the lateral jaw amplitude and duration of jaw opening, which were shorter in the primary dentition group than in adults. Earlier studies also reported that children had a shorter jaw opening duration compared to adults (Kiliaridis *et al.*, 1991; Snipes *et al.*, 1998; Kubota *et al.*, 2010; Yamada-Ito *et al.*, 2013), but the findings for the lateral jaw amplitude were inconsistent. For example, the lateral jaw amplitude was indicated by two studies to be comparable in children and adults (Kiliaridis *et al.*, 1991; Papargyriou *et al.*, 2000), whereas it was indicated to be shorter in children than in adults in another study (Kubota *et al.*, 2010). One viable explanation proposed here is that children's reduced jaw size might be the reason for the shorter lateral jaw amplitude and opening duration in the primary dentition group than in the adult group due to the limitations imposed on the boundaries of lateral jaw movement.

Earlier studies demonstrated that, as the chewing sequence progressed, there was usually a reduction in jaw muscle activity (Peyron *et al.*, 2002; Veyrune *et al.*, 2007; Grigoriadis *et al.*, 2011). In the present work, such reduction was noted in the adult group, where it reached 80-85% at the end of chewing sequence, yet it was not significant in the primary dentition group, where it was just 40% (Figure 16). This suggested that, unlike adults, the primary dentition group had lower adaptation of jaw muscle activity to chewing-related changes in food properties. Several reasons could be cited for such low adaptation, including discrepancies in the histomechanical properties of jaw-closing muscles and periodontium, like reduced diameter and number of muscle fibres (Österlund, Thornell, *et al.*, 2011) and the presumed diminished PMR density in children than in adults as suggested by animal studies (Maeda *et al.*, 1999; Shi *et al.*, 2006; Umemura *et al.*, 2010; Miki *et al.*, 2015). Food cohesion and adhesion characteristics (Iguchi *et al.*, 2015) and its mouthful volume (Goto *et al.*, 2015) can determine chewing behaviour, as they may require greater effort from the jaw-closing muscles to break down into smaller fragments (Kohyama *et al.*, 2007), with implications for the formation of the food bolus (Goto *et al.*, 2015). In this work, the chewing and swallowing of the test food models did not seem to present any obvious challenges to the participants, irrespective of age. While the primary dentition group and the adult group did not differ in the number of chewing cycles and sequence duration, we could draw few speculations based on previous studies. The properties of the food bolus were not examined, but it can be speculated that formation of a pre-swallowing food bolus was achieved by the primary dentition group with a larger mouthful volume. This may suggest that, prior to swallowing it, children may have to separate the food bolus into smaller pieces, so that the jaw muscle activity does not decrease considerably. Moreover, it can be postulated that, unlike the adults, the primary dentition group might have swallowed bigger food pieces, despite effectively chewing and swallowing the test food models. Taken together, the differences in jaw muscle and periodontium histomechanical properties, food mouthful volume and cohesion and adhesion properties of the food could have led to no major changes in the jaw muscle activity with the progression of the chewing sequence in the primary dentition group compared to adults.

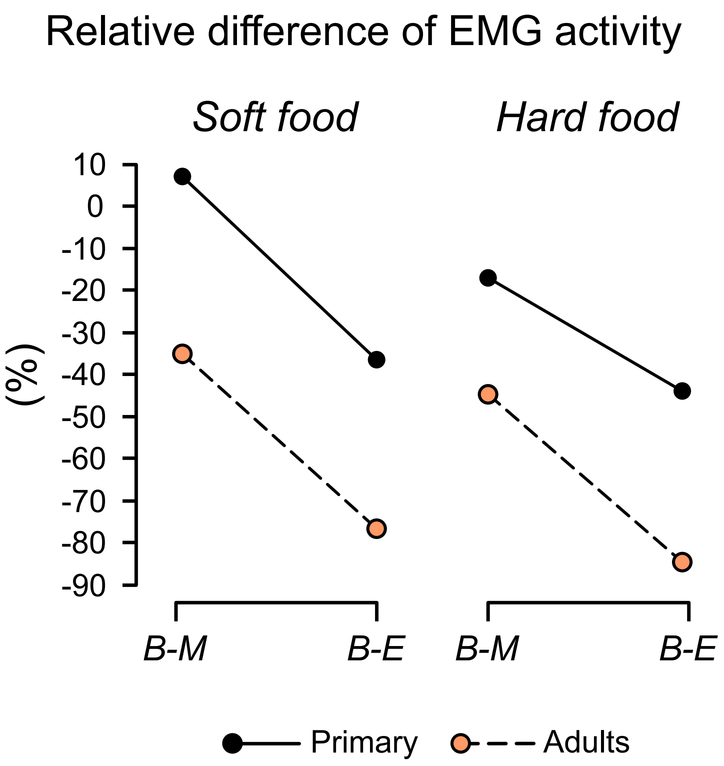


Figure 16. The relative difference (%) of pooled EMG activity (i.e., integrated jaw-closing and occlusal stages) in the primary dentition group and adults during the progression of chewing sequence of soft and hard food models. B-M denotes the relative difference between the beginning and middle segments of chewing regarding EMG activity, while B-E denotes the relative difference between the beginning and end segments of chewing regarding EMG activity.

4.3.2 Age-related changes in food hardness adaptation during chewing

By contrast to the soft food, the hard food required the adult participants to use a higher number of chewing cycles and lengthier chewing sequence duration (Study IV). On the other hand, the number of chewing cycles and chewing sequence duration did not differ significantly according to food hardness in any of the groups of children (Figure 12). However, a low number of chewing cycles and short chewing duration does not automatically imply that chewing is performed effectively (Slavicek, 2010). Instead, proper food pulverisation and food bolus formation are better indicators of effective chewing performance and are in turn affected by the textural characteristics of food (e.g. size, hardness) (Peyron *et al.*, 2002; van der Bilt *et al.*, 2006). Furthermore, the masseter muscle activity was not successfully adapted in the primary, early, late-mixed, and early-permanent dentition groups as food hardness increased at the beginning stage of the chewing sequence. As demonstrated in earlier research, in order to overcome food resistance, jaw muscle activity is usually engaged more intensively by individuals with natural dentition during the first contact between the teeth and food (Ottenhoff *et al.*, 1992). Called additional muscle activity, it is normally associated with the processing of hard food (Grigoriadis *et al.*, 2014, 2019; Grigoriadis & Trulsson, 2018). Hence, chewing behaviour involves adaptation of the jaw muscle activity in keeping with the kind of food being eaten. At the moment, it is assumed that the jaw muscle activity of children in the age range 3-14 years is "immaturely" adapted to food hardness by contrast to children with late-permanent dentition and adults.

Hard food processing was also associated with a lengthier jaw occlusal cycle duration in children aged 3-11 years by comparison to adults. More specifically, whereas it declined by 3% in adults at the chewing sequence end, the occlusal duration increased by around 26% in the primary dentition group, 17% in the early-mixed dentition group, and 9% in the late-mixed dentition group (Figure 17). When contact is first made between the teeth and food, the PMRs disseminate abundant sensory information about the temporal and spatial attributes of the food (Dellow & Lund, 1971; Lund, 1991; Trulsson & Johansson, 1994, 1996a, 1996b; Trulsson, 2006), which is employed by the CNS to regulate the chewing behaviour according to food property changes. Consequently, impairment of PMR sensory input, as in cases of dental implants or dental anaesthesia, lengthens the occlusal cycle duration and prevents the jaw muscles from adapting to increased food hardness (Johansson *et al.*, 2006; Svensson & Trulsson, 2009; Grigoriadis *et al.*, 2011, 2016, 2019; Svensson *et al.*, 2013; Kumar, Castrillon, *et al.*, 2017; Grigoriadis & Trulsson, 2018). The lengthening of the occlusal cycle duration during hard food chewing and unsuccessful adaptation of jaw muscle activity to increased food hardness were observed in the groups of young children in this work. There was no impaired PMR sensory input in those groups, yet the PMRs are likely the reason for the discrepancies in jaw occlusal duration and jaw muscle adaptation, as suggested by histological evidence from studies on animals. Even so, there is no equivalent evidence related to the histological development of PMRs during the transition from primary to permanent dentition. Studies conducted on animals reported that PMRs became denser as the primary dentition transitioned to the permanent one (Maeda *et al.*, 1999; Shi *et al.*, 2006; Umemura *et al.*, 2010; Miki *et al.*, 2015) and that the morphology and development of PMRs were correlated with the eruption of teeth and occlusion development (Umemura *et al.*, 2010; Miki *et al.*, 2015). Extrapolation of such evidence to human beings could result in the theory that primary/mixed dentition is associated with fewer PMRs than the permanent dentition, yielding immature sensory input. This in turn could provide a reason for the lengthier occlusal cycle duration and unsuccessful adaptation of the jaw muscle activity to hard food. There was consistency between the outcomes related to the primary, mixed, and early-permanent dentition groups and the outcomes of *Study III*. It was notably discovered that, unlike adults, the forces employed by children aged 3-14 years for food manipulation between the anterior teeth were higher and showed greater variation (Almotairy *et al.*, 2020). As argued by a recent study, PMRs account for around 20% of jaw muscle activity in the context of chewing (Grigoriadis *et al.*, 2019). Based on this, it can be conjectured that PMRs contribution to chewing in young children may be affected due to their low density, which could explain differences in jaw kinematics and jaw muscle activity.

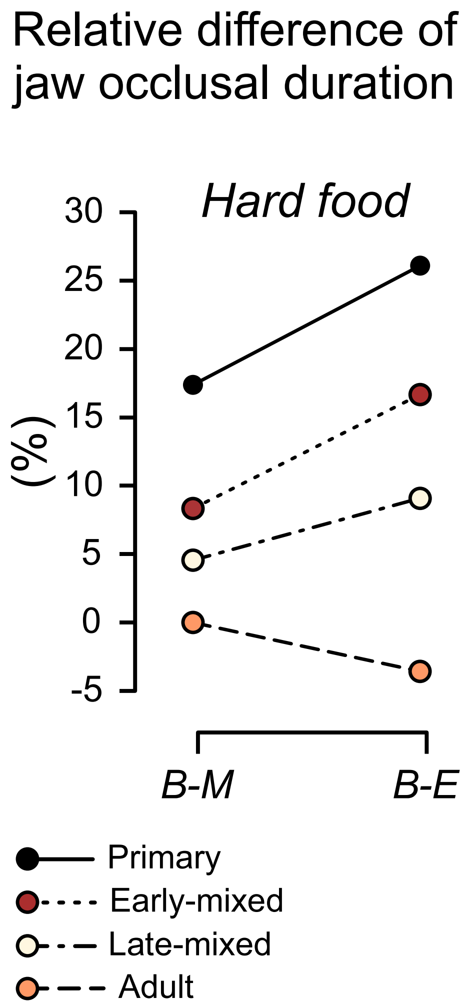


Figure 17. The relative difference (%) of jaw occlusal cycle duration in the primary, early-mixed, and late-mixed dentition groups and adults during the progression of chewing sequence of hard food models. B-M denotes the relative difference between the beginning and middle segments of chewing regarding jaw occlusal duration, while B-E denotes the relative difference between the beginning and end segments of chewing regarding jaw occlusal duration.

5 CRITICAL REMARKS

Methodological concerns are typically present in the clinical and experimental studies of children. Experiments need to be appealing, engrossing, and undemanding to children for clinical research to be successful, especially as children’s attention span is usually shorter than that of adults. Thus, this work has made the effort to ensure that the experiments were pleasant and engaging for the participating children. Images compatible with children’s interests were placed in the laboratory (Figure 18), based on the information about their favourite cartoons and hobbies that was previously gleaned from them during the clinic check-up appointment. Moreover, the children were permitted to draw on a whiteboard with differently coloured markers both pre- and post-experiments. The purpose of such strategies was to enable children to become acquainted with the laboratory setting.

Another issue that can adversely affect experiments is that, unlike adults, children may not be able to understand and achieve task goals effectively. The prospective participating children and their legal guardians received information about the research from two pedodontists with experience and every experimental task was exemplified via video illustrating reliable task performance by a 4-year-old child with proper training in order to improve children’s comprehension. Furthermore, at the start of each experiment (*Studies II* and *III*), both participating children and adults were familiarised with the task to ensure effective performance.

Additional methodological issues may be related to the employed equipment. For instance, *Study IV* involved the use of a jaw tracking apparatus necessitating a magnet to be affixed to the labial surface of the inferior front teeth. To prevent the magnet becoming detached and therefore swallowed by the children, it was affixed externally, underneath the chin. A pilot study was done before conducting the studies to investigate the impact of facial skin stretching during chewing on the ability of the apparatus to precisely track the magnet location. It was observed that the tracking accuracy of the apparatus was not impacted by the differences on magnet location (affixed on the teeth or below the chin).

Figure 18. Measures taken to make the laboratory setting lively and appealing to children.

6 SUMMARY OF MAJOR FINDINGS

Ongoing age-related changes were exhibited by the chewing and biting parameters (e.g. MOBF, jaw kinematics, jaw muscle activity), according to the findings of **Study I**. It was argued that such parameters were underdeveloped in early childhood, but matured with age, with particularly pronounced development at age 10-14 years, when adult-like behaviour starts to emerge. However, it must be remembered that the findings of existing studies might be distorted by confounders like dissimilarities in the employed equipment, food texture properties, and procedures of standardisation and data normalisation. To make up for the gap in knowledge about the age-related changes in the orofacial sensorimotor mechanism underpinning biting and chewing behaviours in children and adults, the present work undertook several studies to assess such changes with regard to unpredictable load changes (Study II), food biting manoeuvres (Study III), and the effect of food hardness on chewing behaviour (Study IV). Figure 19 collates the key conclusions and these are also delineated in the following part.

According to the findings of **Study II**, children and adults without health problems did not differ in terms of the holding forces and force variability in unpredictable yet basic oral force control task, suggesting equal task performance efficiency. Nevertheless, a breakpoint in the outcome variable developmental trends occurred during the late-mixed and early-permanent dentition phases, potentially indicating transition of adult-like oral force control task in these two dentition phases, which was otherwise concealed by the basic nature of the task.

The standardised hold-and-split task in **Study III** involved greater complexity and skill. It was found that the phases of food holding and splitting displayed changes related with age. Compared to adults, the primary, early-mixed, late-mixed, and early-permanent dentition groups employed food holding forces that were higher and more variable. Meanwhile, the food splitting duration was lengthier in the primary and early-mixed dentition groups than in adults, and additionally, those two groups exhibited greater "compensatory" force ramp-increase during the splitting stage. Based on such findings, it was deduced that young children possessed an underdeveloped oral fine motor control in the context of food biting manoeuvres, which became adult-like in the children with late-permanent dentition.

In **Study IV**, the children and adults were required to chew viscoelastic test food models of varying hardness whilst the jaw kinematics and masseter muscle activity were measured. It was found that the number of chewing cycles and the chewing sequence duration did not differ according to age, and neither did the jaw movement vertical amplitude. Nevertheless, compared to adults, the primary dentition group exhibited shorter lateral jaw amplitude and jaw opening duration, whilst also showing higher EMG activity of the masseter muscle at chewing sequence end. Furthermore, the primary dentition group displayed no reduction in the EMG activity as the chewing sequence progressed, irrespective of food hardness. There was a "compensatory" increase in jaw occlusal duration in the primary, early-mixed, and late-mixed dentition groups at the chewing sequence end while eating hard food. In addition, masseter EMG activity adaptation to food hardness increase was unsuccessful in the primary, early-mixed, late-mixed, and early-permanent dentition groups. It was thus deduced that children with primary, mixed, and early-permanent dentition had underdeveloped chewing behaviour.

Moreover, the late-permanent dentition was identified as the phase in which the chewing-related orofacial structures attained complete development and therefore adult-like chewing behaviour could be acquired.

	Study II	Study III		Study IV		
Dental age group	Force control of unpredictable demnad	Food holding	Food splitting	Lateral jaw chewing amplitude	Chewing occlusal duration (hard food)	EMG food hardness adaptation
Primary	+	−	−	−	−	−
Early-mixed	+	−	−	+	−	−
Late-mixed	+	−	+	+	−	−
Early-permanent	+	−	+	+	+	−
Late-permanent	+	+	+	+	+	+

− Non adult-like behaviour
+ Adult-like behaviour

Figure 19. Overview of the key results of Studies II-IV. The achievement and non-achievement of adult-like behaviour are respectively denoted by (+) and (-) for every dental age group.

7 CLINICAL RELEVANCE AND FUTURE PERSPECTIVES

The process of digestion begins with biting and chewing food. Besides supporting the nourishment of the body, these two activities have a number of oral and general body advantages, such as enjoyment of how food tastes and feels, fragmentation of food to make it easier to swallow, activation of food digestion, and increased saliva secretion to facilitate optimal oral health (Chen, 2009). Normal development is accompanied by ongoing transformations in the body in general and in the orofacial structures in particular. The studies undertaken in the present work have attested to the fact that orofacial structure modifications pose difficulties to the sensorimotor control of chewing and biting behaviours, reflecting the adaptation of these behaviours in the structural alterations of healthy children's orofacial structures, similar to other oral motor behaviours (e.g. speech) (Almotairy *et al.*, 2018; Hadders-Algra, 2018).

There is currently no age-related reference value for chewing and biting development, despite the existence of such a value for body height, weight, and head circumference development. This prompted the present work to take on the challenge of identifying the key points in the development of biting and chewing behaviours in healthy children. Such knowledge will be useful for identifying children at risk of chewing problems as a result of a number of orofacial dysfunctions. Orthodontics is one field that could benefit from the findings of this work, as functional abnormalities are a key indicator for orthodontic treatment (Johal *et al.*, 2015). Such treatment is geared towards achieving an aesthetic dental appearance and restoring stomatognathic function, according to the premise that ideal stomatognathic development can be impaired by functional disruptions resulting from aberrant dentition organisation (Bell & Kiebach, 2014). As suggested by earlier research, dysfunctional oral sensorimotor control in biting and chewing may be exhibited by children with orofacial abnormalities, like dental malocclusion. Malocclusion in children has been linked to reduced maximal biting forces (Sonnesen *et al.*, 2001; Castelo, Gaviao, *et al.*, 2010), reduced ability for food fragmentation (Henrikson *et al.*, 1998, 2009), and lack of symmetry of chewing-related jaw muscle activity (Alarcón *et al.*, 2000; Michelotti *et al.*, 2019). In spite of such knowledge, it is still poorly understood how malocclusion and the neural mechanisms underpinning orofacial muscle control are correlated. One particular question to be answered is whether malocclusion affects or is affected by regular oral motor control development.

To address the above question and other significant ones, a range of orofacial and dental abnormalities should be explored in future research regarding their impact on the sensorimotor development of the behaviours of biting and chewing. The findings of such research would be of benefit not only for the identification and diagnosis of sensorimotor dysfunction in biting and chewing, but also for assessment of how successful orthodontic treatment is for restoring biting and chewing behaviours in children.

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The End

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